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Response of the Lower Ord River and Estuary to Changes in Flow and Sediment and Nutrient Loads

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EXECUTIVE SUMMARY

This study, following on from a previous study reported by Parslow et al. (2003a),(2003b), was designed to improve our understanding of how the lower Or River and Estuary function in terms of flow, transport of sediments, nutrient processes, and primary production (i.e., growth of algae and other plants) and to predict how the river is likely to change in response to changes in flows, nutrient and sediment loads that are likely to occur with planned changes in hydroelectric production and water allocation. Questions that the study was designed to answer included:

- How are sediments and nutrients transported through the lower Ord River and its estuary, and what happens to them there?
- What are the sources of food for organisms in the lower Ord River and estuary? Is the foodweb driven primarily by material brought in from the catchment, or by primary production (growth of algae and plants) in the river itself?
- What controls primary production in the lower Ord River and estuary?
- What do we know about the ecology of the system, and what important knowledge do we lack?
- What will happen to the river if water allocation, nutrient or sediment loads change?

The project included monitoring water quality, conducting two intensive field campaigns to study specific processes, and developing conceptual and numerical models of the lower Ord River and Ord River Estuary. These models were then applied to a series of scenarios in order to predict how the system is likely to respond to possible changes in water allocation and management.

Five major zones can be recognised in the lower Ord system, distinguished primarily by their physical properties, but distinct also in their chemical and biological functioning and the habitats they provide for aquatic plants and animals. These are:

1. *Freshwater zone (lower river)*: characterised by unidirectional, fresh water flow with water levels fluctuating according to the volume of water discharged from Lake Kununurra and Dunham River.
2. *Tidal freshwater zone*: predominantly freshwater, but water levels rise and fall under the influence of tides.
3. *High energy brackish zone (turbid mid estuary)*: influenced by freshwater discharge, vigorous tidal currents and a change in salinity, this is a region with high suspended sediment loads and high turbidity (i.e. low water clarity).
4. *Tide-dominated estuarine zone (estuary mouth)*: characterised by salinity approaching that of seawater, and lower turbidity than the high energy brackish zone upstream
5. *Tidal creeks and flats zone*: the area of mudflats and creeks off to the side of the main estuary channel, sometimes having lower turbidity than the open estuary

A conceptual model is presented to illustrate our present understanding of how these zones interact, and how the lower river and estuary function as a system.

Primary production (i.e. production of plant biomass) in the freshwater zone appears to be phosphorus-limited, and dominated by benthic plants and algae growing on plants and on the river bottom. Net system metabolism is close to neutral in this zone. Primary production in the high energy brackish zone is low, limited by light and the strong salinity gradient. Production in the estuary mouth is again limited by nutrients.

The numerical models developed for this project have been applied to a series of management scenarios to explore the likely effects of changes to water allocation and flow. These scenarios included 1) current conditions; 2) increased discharge from the hydroelectric dam; 3) increased hydroelectric discharge combined with increased extraction for irrigation; 4) 50% reduction in irrigation return flows; 5) 100% reduction in irrigation return flows, and 6) a return to interim Environmental Water Provisions Braimbridge, M. and Malseed, B. (2007).

The model suggested that scenario 6 would make little difference to water quality (nutrient concentrations, turbidity or growth of algae), scenarios 4 and 5 would lead to improvements in water quality (reduced nutrient and chlorophyll *a* concentrations) and possibly increases in fish production, and scenarios 2 and 3 would both have mixed results for water quality. Scenario 2 might lead to a reduction in fish production while scenario 3 might lead to an increase in fish production.

Scenario predictions for fish are based on a preliminary foodweb model and are highly speculative as they do not include habitat effects and are based on limited information about the higher-level ecology of the lower Ord River, particularly in the estuary.

Major knowledge gaps remain regarding the ecology of the estuary, interactions between the lower river and its floodplain, and the likely response of the system to changes in climate and sea-level.

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1. INTRODUCTION

The Ord River, located in north Western Australia near the border with the Northern Territory (Figure 1), is a unique system. The river is valued for its inherent beauty, diverse ecosystem, Aboriginal and non-Aboriginal heritage, recreational utility, tourism, fisheries, and for the water it carries. The river has been dammed in two places to create Australia's second-largest reservoir, Lake Argyle, and to provide water for a hydroelectric generator providing power to the Argyle diamond mine and the towns of Kununurra and Wyndham, and water for the Ord River irrigation scheme Trayler, K. et al. (2003a).

The river downstream of the Argyle and Kununurra dams has changed substantially over the past forty five years in response to changes in flow, and there is some evidence Wolanski, E. et al. (2001),Wolanski, E. (2006) that the river is still gradually adjusting to these changes. The most significant change is that the Ord River now flows all year around, whereas before the dams were built, there was very little flow in the river during the long dry season, while flood events during the wet season would have been larger and more frequent Department of Water (2006). In flowing throughout the year, the Ord River in its current form is unusual among rivers in Australia's tropical north.

With ongoing drought in the south, Australia's attention is turning to the development potential of the north more than ever before. Current proposals for the Ord River include increasing the area of irrigated land supplied by the river, increasing the production of the hydroelectric dam, and installation of a tidal power station in the estuary. Any of these changes would change the way water moves into and through the lower river and estuary, and change the load of sediments and nutrients associated with this water.

To manage the river wisely, we must understand the physical, chemical, and biological processes that underpin the ecological and aesthetic characteristics that we value. With this understanding, we can make predictions about how the river is likely to change when environmental conditions change.

This study, following on from a previous study reported by Parslow et al. (2003a),(2003b), was designed to improve our understanding of how the lower river and estuary function in terms of flow, transport of *sediments*[1], *nutrient* processes, and *primary production* (i.e., growth of algae and other plants) and to predict how the river is likely to change in response to changes in flows, nutrient and sediment loads.

Primary production is important because plants form the basis of the foodweb, driving production of fish and other animals in the river and also influencing the habitat. Changes is the amount or type of primary production lead to changes in the number and type of fish and other animals supported, and too much primary production can lead to problems such as algal blooms.

Suspended sediments reduce the penetration of light into the water, reducing growth of plants and algae, and influencing the physical habitat of animals in the river. Suspended sediment concentrations in the estuary of the Ord River are naturally high, giving the water a muddy appearance. Increased suspended sediment loads can lead to filling-in of the river channel, increased nutrient loads, and reduced primary production.

Questions that this study was designed to answer included:

- How are sediments and nutrients transported through the lower river and estuary, and what happens to them there?
- What are the sources of organic matter in the lower Ord River and estuary? Is the foodweb driven primarily by material brought in from the catchment, or by primary production (growth of algae and plants) in the river itself?
- What controls primary production in the lower Ord River and estuary?

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[1] Italicised words are among those explained in the glossary at the back of the report.

- What do we know about the ecology of the system, and what important knowledge do we lack?
- What will happen to the river if water allocation, nutrient or sediment loads change?

The project included monitoring water quality, conducting two intensive field campaigns to study specific processes, and developing *conceptual* and *numerical models* of the lower Ord River and Ord River Estuary. These models were then applied to a series of scenarios in order to predict how the system is likely to respond to possible changes in water allocation and management.

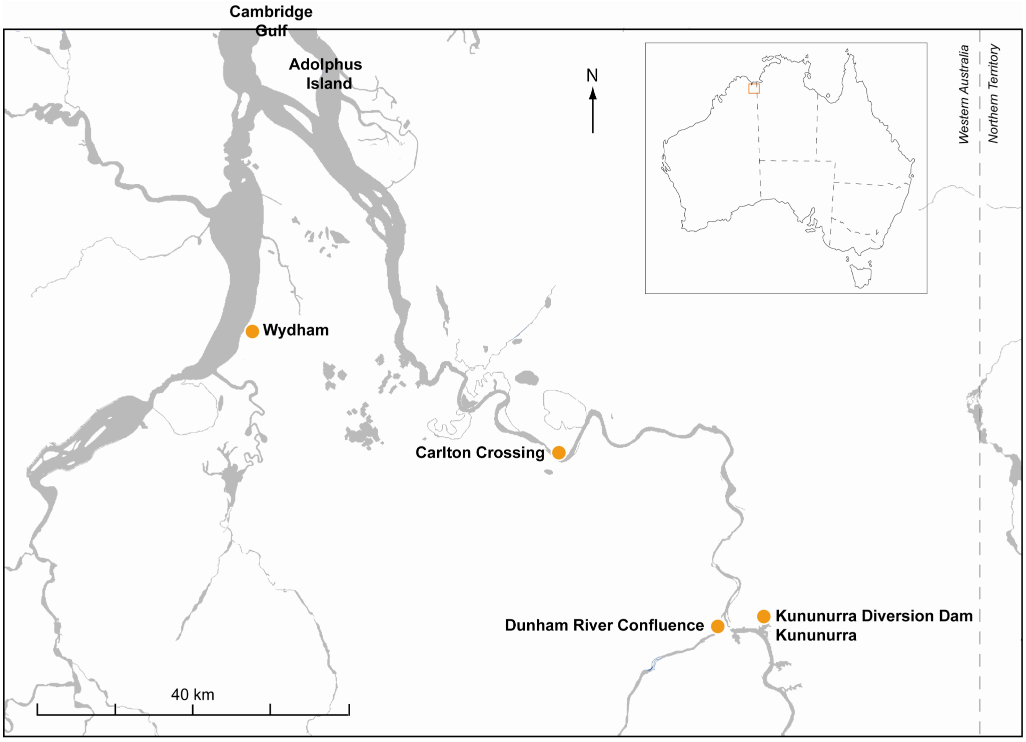

Figure 1 The lower part of the Ord River and its estuary. This study covered the region from Adolphus Island, just south of Cambridge Gulf, to Kununurra Diversion Dam. The west arm of the estuary, running past Wyndham, was not included in the study.

2. METHODS: MONITORING, FIELD CAMPAIGNS, NUMERICAL MODELS

The project included five main components:

1. **Synthesis of existing ecological data and identification of knowledge gaps.**

   The results of this work are outlined briefly in Section 4 and discussed in detail in a separate technical report Gehrke, P. (2008).

2. **Regular monthly monitoring of water quality in the estuary to complement ongoing monitoring in the lower Ord River.**

   This included taking water samples at several sites each month to measure nutrient concentrations[2], salinity, temperature, chlorophyll *a* (a measure of the amount of algae in the water), oxygen concentrations, and measures of water clarity.

   Figure 2 shows the regular water quality monitoring sites including in this study. More details, including details of site locations, are given in Appendix 1.

3. **Wet-season and dry-season field campaigns designed to answer specific scientific questions about how the lower Ord River and Estuary function, physically, chemically, and biologically.**

   This included:

   - Measurements to characterise organic matter and carbon sources in the river and estuary (to improve our understanding of the basis of the foodweb);
   - Sampling of water quality at a number of sites not included in the regular monitoring programme, including tidal salt creeks;
   - Sampling of sediments from several sites to better characterise the physical nature of the river bed and nutrient content of sediments;
   - Measurements and incubations to enable estimates of primary production (growth of algae in the water and on submerged surfaces) and system metabolism (the balance between oxygen production by plants including algae, and oxygen consumption by bacteria, animals, and chemical processes in the river);
   - Measurements of algal photosynthetic activity and the degree to which algal growth was constrained by light and nutrient availability;
   - Measurements to identify algal-bacterial interactions; and
   - Measurements of the physical environment of the river, including water velocity and water depth over the course of the tidal cycle, the shape of the river bed in tidal creeks, and changes in salinity, temperature and turbidity (a measure of water clarity) over the course of the tidal cycle.

     Measurements of rate processes, such as primary production, photosynthetic activity, and metabolism were undertaken at three sites on the first sampling trip (August 2006) and four sites on the second sampling trip (February 2007) spanning the freshwater reaches of the Ord R. through to Cambridge Gulf. The number of sites measured was limited due to logistical and cost

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[2] Nutrient measurements including total nitrogen (TN), total kjeldal nitrogen (TKN), soluble organic nitrogen (DON), ammonium (NH_3/NH_4), dissolved nitrate (NO_2), soluble oxidised nitrogen (NO_x), total phosphorus (TP), soluble organic phosphorus (DOP) and soluble reactive phosphorus (PO_4) as well as soluble reactive silica (SiO_2). Total and dissolved organic carbon (TOC and DOC) were also monitored, along with alkalinity, pH, turbidity, total suspended solids (TSS), dissolved oxygen, Secchi depth, phaeophytin, chlorophyll *a, b* and *c*, temperature, chloride, conductivity, and salinity (calculated from conductivity).

constraints. However, this information is assessed in conjunction with the water quality measures which provide a more comprehensive data set over space and time. This allowed a comparison of rate processes between the river, estuary and Gulf to provide insights into the key factors limiting the productivity of the system.

These measurements are not described in detail in this plain English project report, but will be described and discussed in a forthcoming technical report and series of scientific papers. A summary of the methods used and key findings is given as Appendix 2.

4. **Development of conceptual models describing how the lower river and estuary function, and how physical, chemical and biological processes interact to produce the patterns we see.**

   These are described in Sections 3 and 5.

5. **Development of numerical models (computer models) to simulate the flows, sediment and nutrient processes in the river and estuary, as well as links between nutrient processes and ecology in the freshwater zone.**

   These models were then applied to a series of management scenarios to explore how the lower Ord River and estuary are likely to respond to management and water allocation changes being considered for the near future.

   Details of these scenarios and the results of scenario modelling are discussed in Section 6. Details of model implementation and validation will be described in a forthcoming technical report, but a few brief technical details are given in Section 6.1 for those interested.

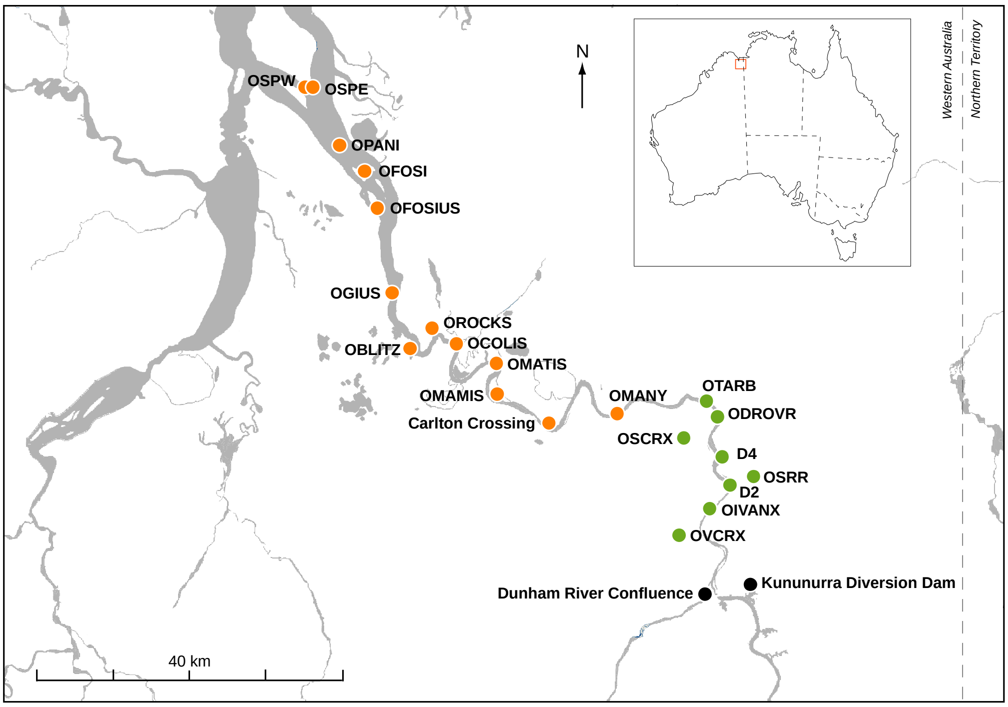

Figure 2 Regular monitoring sites in the lower Ord River and Estuary. Orange dots show sites monitored as part of this study; green dots show some regular Department of Water monitoring sites, the data from which were also used in this study.

3. THE LOWER ORD RIVER AND ESTUARY: A DESCRIPTION OF FIVE ZONES

Five major zones (Figure 3) can be recognised in the lower Ord system, distinguished primary by their physical properties, but distinct also in their chemical and biological functioning and the habitats they provide for aquatic plants and animals. These are:

1. *Freshwater zone (lower river)*: characterised by unidirectional (non-tidal), fresh water flow with water levels fluctuating according to the volume of water discharged from Lake Kununurra and Dunham River.
2. *Tidal freshwater zone*: predominantly freshwater, but water levels rise and fall under the influence of tides.
3. *High energy brackish zone (turbid mid estuary)*: influenced by freshwater discharge, vigorous tidal currents and a salinity intermediate between freshwater and sea water, this is a region with high suspended sediment loads and high turbidity (i.e. low water clarity).
4. *Tide-dominated estuarine zone (estuary mouth)*: characterised by salinity close to that of seawater, and lower turbidity than the high energy brackish zone upstream
5. *Tidal creeks and flats zone*: the area of mudflats and creeks off to the side of the main estuary channel, sometimes having lower turbidity than the open estuary

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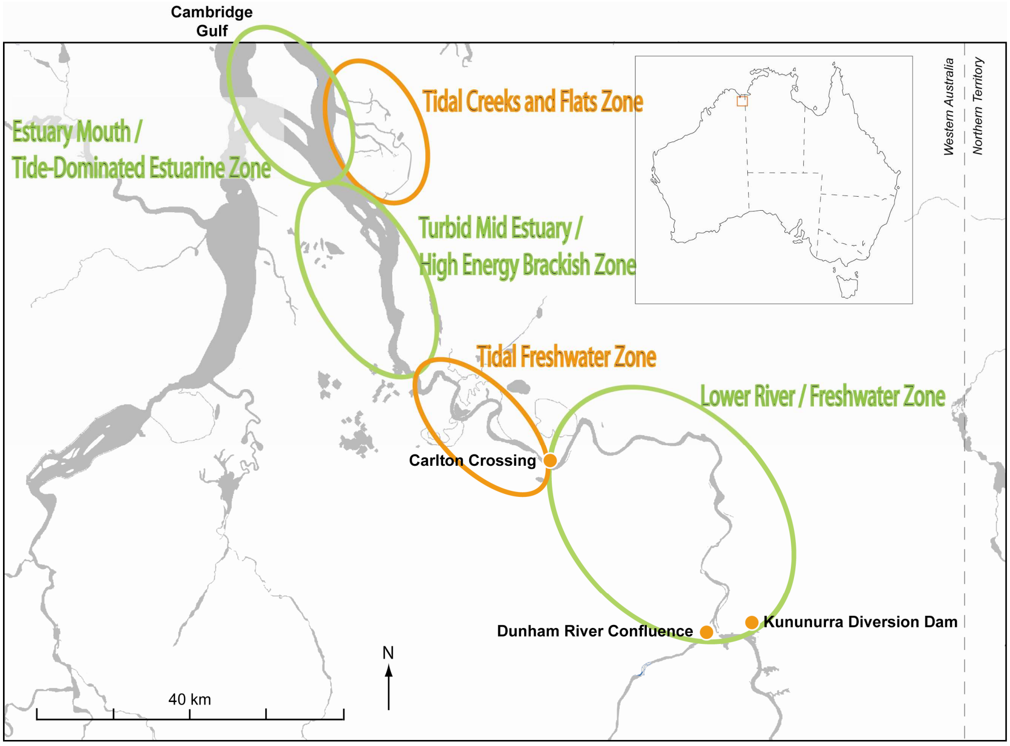

Figure 3 Approximate extents of five zones of the lower Ord River and estuary

3.1. The freshwater zone (lower river)

Figure 4 The lower river, upstream of the tidal limit

Immediately downstream of Kununurra Diversion Dam and extending as far downstream as Carlton Crossing is a stretch of river that is not strongly influenced by the estuary. The water in this zone is fresh, and in the dry season, clear, with turbidity consistently close to zero.

Most previous studies in the lower Ord have focused exclusively on this zone, so there is considerably more ecological data available for this region than for the estuary. An exception was the precursor to this study Parslow, J. et al. (2003a),Parslow, J. et al. (2003b), which focused on the section downstream of Carlton Crossing.

The river is relatively shallow, with depths of only a few metres, throughout most of the lower river and estuary, but in the freshwater zone, there are a few deeper pools. Without releases from the Kununurra Diversion Dam, this part of the river would probably have functioned during the dry season as a series of loosely connected pools.

The river is relatively narrow in the freshwater zone, with varied fringing vegetation providing a range of habitats, and the river bed dominated by gravel and rock interspersed with sandy sections. Rushes grow in shallower, more silty parts of the river bed, though these areas are dynamic and probably rearranged with every large flood. The vegetation and habitats of this part of the river have been described and mapped in detail by Storey (2002),(2003),(2008) and are also discussed by Gehrke (2008). In-stream vegetation includes areas of *Phragmites*, typha and ribbonweed Storey (2008).

Flow and water quality in the freshwater lower river are controlled by releases from the dam, flows from Dunham River, and inputs from the irrigation drains just downstream of Dunham River. During the dry season (typically from April to October), the dam is the main source of water, with flows typically maintained at around 50 to 60 m^3s^{-1}, but allowed to fall to 33 to 42 m^3s during droughts. Water takes 4 to 9 days to travel from the dam to Carlton Crossing at these flow rates, and during this time, nutrients are subject to a variety of biological and chemical processes such as uptake by plants and algae to fuel their growth.

A substantial proportion of dissolved inorganic nutrients entering the freshwater zone of the lower Ord River during the dry season are lost or transformed to other forms before reaching the estuary (Figure 5). Dissolved inorganic nutrients are quickly taken up by algae, whereas particulate and organic nutrients need to be broken down by bacteria or passed through the food chain before they can be used by algae, so rivers including the Ord are more sensitive to inputs of dissolved inorganic nutrients than to particulate or dissolved organic nutrients.

Irrigation drain return flow contributes only around 2 to 5 m^3s^{-1} to dry season flows in the lower Ord River, but a relatively higher proportion of the total nutrient and sediment loads (Figure 5). During the dry season, we estimate that irrigation drain return flow accounts for about one third of the total nitrogen load and almost one quarter of the total phosphorus load, and for approximately half the load of dissolved inorganic nitrogen and phosphorus entering the lower river. These load estimates were calculated using the load-flow relationships described in Section 6.2.2, and the flows associated with the “typical flow year” scenario in that section.

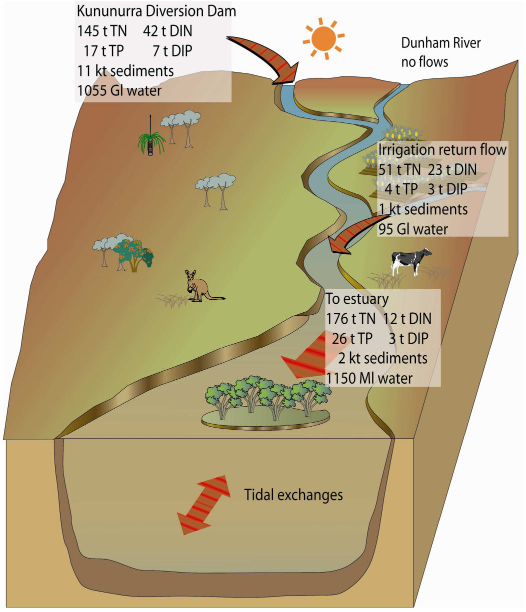

Figure 5 Inputs of nutrients (total nitrogen – TN, total phosphorus – TP, dissolved inorganic nitrogen – DIN and dissolved inorganic phosphorus – DIP) and sediments to the lower Ord River during the dry season during a typical year. Values are as calculated for the period from June to January for the “current conditions, typical flow year” scenario.

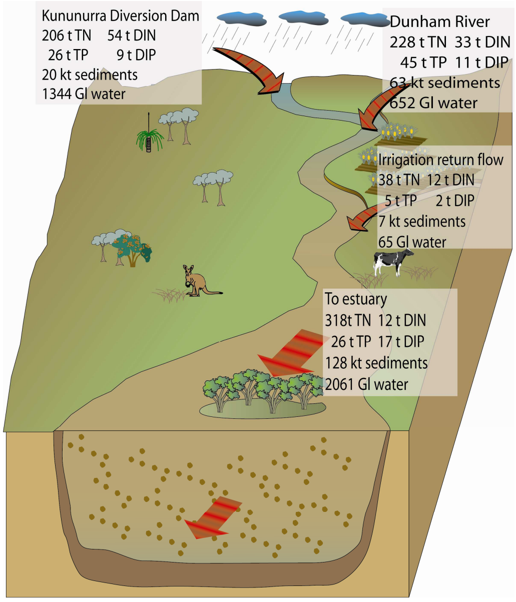

Figure 6 Inputs of nutrients and sediments (total nitrogen – TN, total phosphorus – TP, dissolved inorganic nitrogen – DIN and dissolved inorganic phosphorus – DIP) to the lower Ord River during the wet season during a typical year. Values are as calculated for the period from February to May for the “current conditions, typical flow year” scenario. Flow volumes and associated wet-season nutrient and sediment loads for a wet year may be three to five times those shown.

During the wet season, nutrients and sediments enter the river at a much greater rate, along with increased flows, particularly from Dunham River (Figure 6). Irrigation return flow makes up only a small proportion of the nutrient and sediment load during high-flow periods, but flows in the river during the wet season are high (sometimes exceeding 800 m^3s^{-1}), so materials entering the river spend only a few hours in the river, and little biological uptake or transformation occurs in this time.

Our models suggest that a substantial proportion of the sediment load during the dry season settles temporarily to the river bed in the freshwater zone, and is not immediately delivered to the estuary. During high-flow periods in the wet season, this sediment is scoured out and carried downstream along with fresh sediment material from the catchments.

During flood events, a great deal of particulate material – from soil to whole trees – is washed into the river, water levels are elevated, rushes and other river plants may be ripped out by high flows, and the water is likely to have a muddy appearance throughout the river. As flood waters recede, however, water in the freshwater zone clears relatively quickly.

3.2. The tidal freshwater zone

Figure 7 The freshwater tidal zone

This region downstream of Carlton Crossing is also characterised during the dry season by clear, fresh water, though it is a little more turbid than the freshwater zone described above. As is true upstream of Carlton Crossing, water in this section usually flows in one direction: from upstream to downstream, though the water level rises and falls with the tides. The river bed varies from silty sand to gravel in this section, but does not appear to have the sections of solid rock that occur in parts of the freshwater zone.

This part if the river is a quite different physical environment from the freshwater lower river because it is subject to tidal variations in water level and conductivity, with water levels typically varying by about 1.5m over the course of each tidal cycle. Muddy river banks are exposed at low tide, providing a habitat for benthic microalgae and animals such as crocodiles.

Even during the dry season, a typical parcel of water spends only around 60 hours in this part of the river before being flushed downstream by river flow and tidal mixing[3].

Concentrations of phytoplankton (algae) in the water tend to be higher in this zone than upstream[4], simply because phytoplankton have had some time to grow by the time they reach this part of the river. Growth rates of phytoplankton and epiphytes (algae growing on surfaces such as larger plants) in the freshwater parts of the lower river and estuary is limited primarily by phosphorus concentrations: in other words, increased phosphorus loads would lead to more algal growth in this zone.

Nutrient concentrations in the tidal and non-tidal freshwater zones tend to be quite low during the dry season[5].

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[3] Approximate residence time calculated as twice the period taken for the concentration of a tracer initialised to a value of 1 in this zone (and 0 elsewhere) to fall to a mean concentration of 0.5 in this zone, given a flow rate of 50 m^3s^{-1}.

[4] Typically up to 5-10 mg chl *a* m^{-3}, though occasionally up to 20 mg chl *a* m^{-3}.

[5] Typically around 10 mg DIP m^{-3} and 70 mg DIN m^{-3} in the freshwater zone, around 8 mg DIP m^{-3} in the tidal freshwater zone.

A description of this zone in ecological terms is provided in the Ecological Synthesis Report of this project Gehrke, P. (2008), although this zone has been less well studied that the freshwater zone.

3.3. The high energy brackish zone (turbid mid estuary)

Figure 8 The turbid mid estuary

Downstream of the tidal freshwater zone, the river changes dramatically. The estuary opens out, becoming wider and in some sections very shallow. The river bed is dominated by silt and clay, and large quantities of fine sediments are continually picked up and redeposited by very active tidal currents. The direction of flow depends on the phase of the tide, and tidal velocities sometimes exceed 1 ms^{-1} (3.6 km h^{-1}). A tidal range of 5 m is observed at *spring tides*; consequently large tidal mudflats exist along the edges of the river. A parcel of flowing into this zone during the dry season would traverse it within about 3 days[6].

This region is characterised by very muddy water[7] and elevated nutrient concentrations[8]. The majority of the nitrogen and phosphorus in this zone is in particulate form, part of the mass of detritus and mineral material resuspended from the sediments by strong tidal currents. This particulate nitrogen and phosphorus is not readily available to algae and other plants, nor is the majority a particularly good food source for animals.

The highest sediment and nutrient concentrations coincide with a sudden change in salinity as fresh river water meets sea-water. This contributes to the high suspended sediment concentrations as salinity influences precipitation, *flocculation* and aggregation of sediment particles, and hence affects the resuspension of sediments[9].

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[6] Approximate residence time calculated as twice the period taken for a tracer initialised to 1.0 in this zone (and zero elsewhere) to fall to an average concentration of 0.5 in this zone, given a freshwater flow rate of 50 m^3s^{-1}.

[7] Turbidity >>100 NTU, measured total suspended solids concentrations from 10 to 1800 mg L^{-1}.

[8] Typically around 60 mg m^{-3} total phosphorus, 200-500 mg m^{-3} total nitrogen

[9] Salinities in this report are reported using the (unitless) practical salinity scale, corresponding effectively to parts per thousand.

Dissolved inorganic nutrient concentrations are also often elevated[10] in this part of the estuary in comparison with other zones. This appears to be due to the release of nutrients by dying algae. Although concentrations of phytoplankton (measured as chlorophyll *a*) are sometimes higher here[11] than anywhere else in the system, this phytoplankton appears to be at the end of its life, not capable of actively growing even if light and nutrients are provided. We believe that this is due to the sudden change of salinity in this region. Most of the algae here is fresh-water phytoplankton washed in from the river upstream, and not adapted to life in sea water. Marine phytoplankton cannot get a foothold in this zone because there is insufficient light in the muddy water.

It was hypothesised at the beginning of this study that the tidal mudflats might be a rich source of primary production by microalgae, but we found only limited areas where this was the case, with many areas having insufficient bank stability for microalgae to become established.

3.4. The tide-dominated estuarine zone (estuary mouth)

Figure 9 The estuary mouth

As the river passes Adolphus Island and joins Cambridge Gulf, the estuary becomes very wide; approximately 8 km wide just upstream of Adolphus Island, the northern limit of our study. Water clarity varies over the tidal cycle, but the water is generally much less muddy[12] than in the turbid mid estuary. The water in this region is consistently salty (approaching the salinity of seawater)[13] during the dry season, and the tidal range is approximately 7 m at spring tides. A parcel of water entering this part of the estuary during the dry season would, on average, remain in this zone for only about 19 hours[14], due to vigorous tidal mixing.

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[10] Dissolved inorganic phosphorus concentrations up to 50 mg m^{-3}, nitrate concentrations up to 250 mg m^{-3}.

[11] Often around 10 mg chl *a* m^{-3} and occasionally up to 20 mg chl *a* m^{-3}.

[12] Turbidity<200 NTU

[13] From 28 to seawater (35, on the practical salinity scale).

[14] Approximate residence time calculated as twice the period taken for a tracer initialised to 1.0 in this zone (and zero elsewhere) to fall to an average concentration of 0.5 in this zone, given a freshwater flow rate of 50 m^3s^{-1}.

Chlorophyll *a* concentrations (concentrations of algae) are generally quite low in this region, and nutrient concentrations are also lower than in the zone upstream. Growth of phytoplankton appears to be controlled by nitrogen (meaning that there is a shortage of dissolved nitrogen relative to phosphorus) and the combination of periodically low light penetration and vigorous tidal agitation of the bottom prevents growth of algae and other plantson the bottom.

Sediments on the mudflats are generally sandy with a component of silt, while clay appears to dominate the sediments of the channel bed.

Tides in the estuary are asymmetric, with water moving more quickly upstream on the *flood tide* than it moves downstream on the *ebb tide*. A consequence of this is that more sediment material is picked up by the flow tide and transported upstream than is picked up and transported downstream by the ebb tide: in other words, the tides tend to transport fine sediments into the estuary from downstream rather than out the estuary mouth into the sea during the dry season. This effect, in combination with reduced wet-season flows, seems to be resulting in a gradually filling-in of the estuary with silt Parslow, J. et al. (2003a),Parslow, J. et al. (2003b),Wolanski, E. et al. (2001),Wolanski, E. (2006).

Dissolved nutrients, by contrast, remain in the water over the whole tidal cycle, and are transported out of the estuary by tidal mixing.

During the wet season, high flows sometimes push fresh water all the way to the mouth of the estuary, and carry large loads of sediments out into the sea. From one year to the next, the area is quite dynamic, with flood flows altering the path of the estuary channel, washing away some small mangrove islands and forming new islands.

3.5. The tidal creeks and flats zone

Figure 10 Tidal creeks and mudflats in the Ord River, near the northern entrance of Connection Loop

The final zone is the network of tidal creeks fringing the northern part of the estuary, including – but not limited to – the large area highlighted under this label in Figure 3. These creeks are characterised by relatively high salinities (similar to those observed in the estuary mouth), variable (but generally low) water clarity, a large edge area of mudflats, and mangrove vegetation. Several islands in the lower estuary exhibit the same characteristics, and can also be considered part of this zone.

This area supports a distinct ecosystem, including the mangroves themselves and mudflat animals such as crabs and mudskippers. The large edge-area may be significant for nutrient cycling, but this requires further study.

Notable among the tidal creeks is Connection Loop, which joins the main estuarine channel at both ends, connecting to the tide-dominated estuarine zone at its northern end and the high-energy brackish zone at its southern end. Salty, estuary-mouth water mixes into Connection Loop from the northern end during flow tide, and is to some extent displaced by less salty estuarine water from the southern end during the ebb tide. Dissolved oxygen concentrations, influenced by the effect of salinity on the *saturation oxygen concentration*, also vary over the *semi-diurnal* tidal cycle.

4. ECOLOGY OF THE LOWER RIVER AND ESTUARY

The ecosystem of the lower Ord River and estuary is driven by a tropical climate with strong wet and dry seasonal cycles, modified by episodic floods. The operation of Kununurra Diversion Dam and Ord River Dam upstream moderate the natural flow cycle. This results in a river that possesses many characteristics of a Wet Tropics river, rather than a dry savannah river, with dry-season flows higher than the natural level and reduced flood frequency.

The river supports a diverse ecosystem, including many species of fish and birds, plants and algae, salt water and fresh water crocodiles, turtles, shellfish and aquatic insects. As part of this study, existing information about the ecology of the river has been reviewed in a technical report by Gehrke (2008), who also identifies important gaps in our knowledge about the ecosystem, and makes recommendations for monitoring.

Each of the five functional zones supports a different food web because of the differing effects of light and nutrient availability, physical habitats, structural habitat offered by littoral vegetation, contributions to food webs of material transported from other zones or from riparian habitats or species which migrate through these zones.

A preliminary ECOPATH food web model for the freshwater zone, developed for this study and described by Gehrke (2008) supports earlier studies in the Ord that suggest algae are the most important food source for food chains in this zone, rather than terrestrial sources. Food chains appear to be short and omnivory is wide-spread.

The ecological synthesis study Gehrke, P. (2008) highlights many gaps in the information available to describe the ecology of the lower Ord River, especially in the estuary. Quantitative studies of biodiversity and species distributions across the different zones are required to provide benchmarks against which future changes may be assessed. Long-term monitoring of fish and other key species, and more detailed investigations of biodiversity and species distributions across habitats will allow changes in system status to be detected and to trigger more detailed investigation and management actions.

Additionally, a better understanding of climate-change scenarios, hydrological and sedimentary risks, especially in the estuary, and implications for habitat dynamics and biodiversity is required. Floodplains are generally believed to play an important role in the productivity of riverine ecosystems, but the role of the Ord floodplain and consequences of flow regulation for this have not been studied.

5. CONCEPTUAL MODELS: HOW DOES THE RIVER FUNCTION?

This section draws together and summarises concepts introduced in Section 3 to present a picture of our current understanding of how the lower Ord River and estuary functions as a system with respect to the transport and transformation of sediments and nutrients.

During flood events in the wet season (Figure 11), large volumes of water flow into the lower river from the catchment, primarily via the Dunham River and as overflow from the Kununurra Diversion Dam. This flood-water flushes the system with freshwater all the way to the mouth of the estuary, and carries with it large quantities of sediments and nutrients. Additional sediments are scoured from the river bed. Plant beds are ripped up by the strong currents, and islands in the mouth of the estuary are sometimes rearranged.

Although we were not able to study the river during a large flood event, high flows mean that water and the associated sediments and nutrients spend only a few hours in the lower river and estuary during flood conditions, and little transformation is likely to take place in this time, especially given the turbid conditions, which do not allow enough light to penetrate the water for algae to grow.

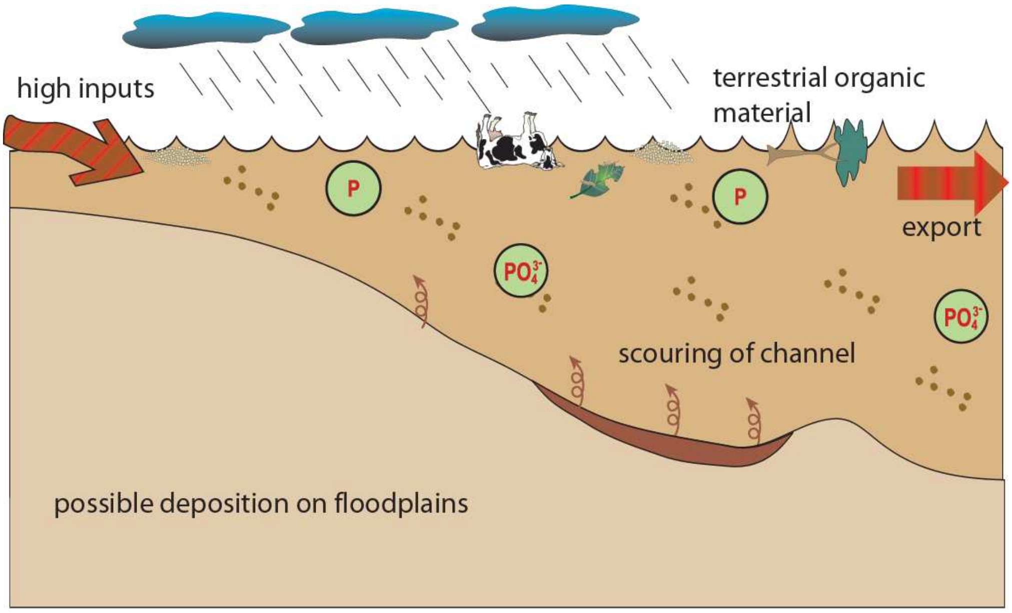

Figure 11 The lower Ord River and Estuary during the wet season

As flood flows subside, the water level falls and sediments drop out of the water. During the dry season (Figure 12), releases from the Kununurra Diversion Dam maintain flows between 50 and 80 m^3s^{-1}, which may be allowed to drop to 42 m^3s^{-1} during droughts. The water is clear in the freshwater part of the lower river and estuary, but remains turbid in the mid estuary due to continual resuspension of sediment material by strong tidal currents. The maximum sediment concentration occurs at a salinity of about 5, where flocculation plays an important role in particle settling behaviour.

Asymmetrical tidal currents tend to bring additional sediment material into the estuary from Cambridge Gulf.

In dry-season conditions, primary production (plant and algal growth) in the freshwater zone is controlled by low concentrations of dissolved phosphorus (Figure 13). Concentrations of algae in the water are generally low relative to the concentrations that would be required for rapid growth of algae. Algae growing on rocks and plants contribute a significant component of total system production, and are an important source of food at the base of the foodweb.

Net system metabolism in the freshwater zone is close to neutral, i.e. oxygen production by growing algae and plants is balanced by oxygen consumption by bacterial processes, animals and plant respiration. Any phytoplankton production is being eaten as fast as it grows.

A substantial proportion of the nutrient load reaching the river during the dry season is contributed by irrigation return flows that drain into the river downstream of Dunham River, with the balance contributed by releases from Kununurra Diversion Dam.

In the high-energy estuarine zone, particulate nutrients are resuspended from the sediments and concentrations of dissolved inorganic nutrients are also a little higher than upstream. Low light penetration precludes plant growth in this part of the estuary channel, and freshwater phytoplankton washed into this area are killed by increased salinity, releasing nitrogen and phosphorus into the water. Respiration exceeds oxygen production in this zone: bacterial processes use up oxygen faster than it is produced by plants.

At the estuary mouth, the water is less muddy and light is able to penetrate further, but algal growth is controlled by lower concentrations of nitrogen (and perhaps phosphorus) in forms available to plants.

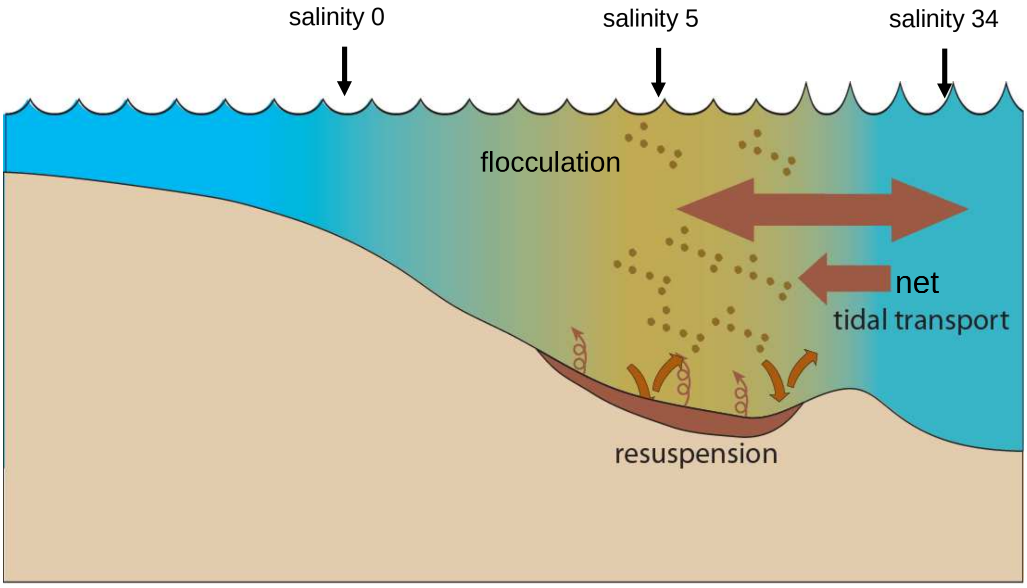

Figure 12 Sediment transport in the lower Ord River and estuary during the dry season

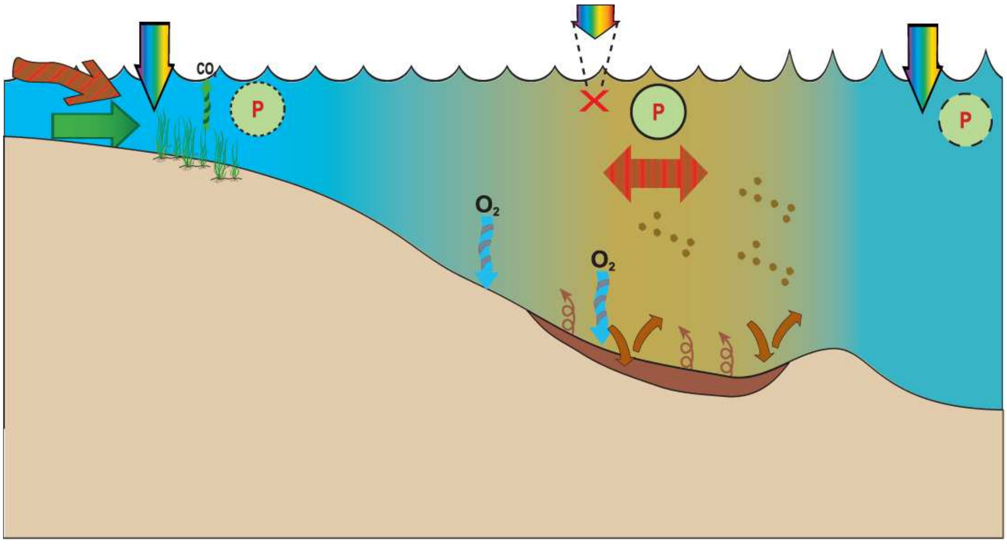

Figure 13 Primary production in the lower Ord River and estuary during the dry season

6. MODELLING OF MANAGEMENT SCENARIOS

6.1. The models

6.1.1. The biogeochemistry model

The Environmental Modelling Suite (EMS, Herzfeld, M. et al. (2005),Sakov, P. (2005),Margvelashvili, N. et al. (2002)) simulates in-stream *hydrodynamic* transport of nutrients and sediments, and cycling of nitrogen and phosphorus (biogeochemistry), including lower-level interactions with plants and small animals. In simple terms, it simulates flow and water quality. A brief technical description is included here for those interested.

In this study, EMS (Figure 14) was applied to simulate the hydrodynamics, sediment dynamics and *biogeochemistry* of the lower river and estuary.

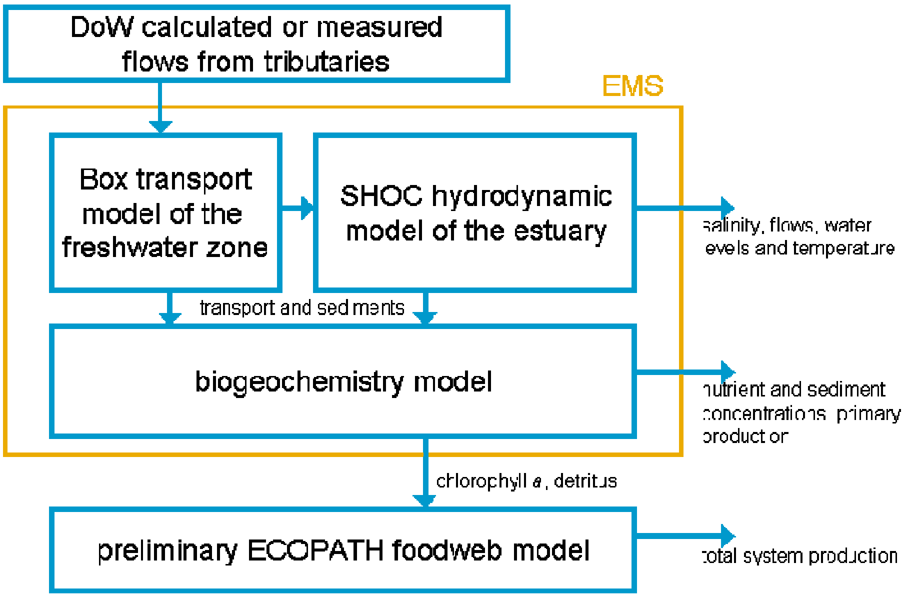

Figure 14 Relationship between the models used in this study

Transport

For the estuary (downstream of Carlton Crossing), a one-dimensional version of the hydrodynamic model, SHOC Herzfeld, M. et al. (2005) version 841 was applied, using the parameterisations for hydrodynamics developed for the Ord River Estuary in an earlier study by Parslow et al (2003a),(2003b). Water was assumed to be well-mixed vertically and across the width of the channel and the length of the estuary was represented as a set of 45 cells, each 2km long.

For the river upstream of Carlton Crossing, breaks in river topography meant that SHOC was not appropriate, so the EMS box transport model was used, supported by water levels predicted by the one-dimensional hydrological model, HEC-RAS (Horritt, M.S. and Bates, P.D. (2002). The same biogeochemical model was applied to this part of the river as was used with SHOC for the estuary.

Sediment dynamics

The sediment model was based on the model and parameterisations developed for the Ord River estuary by Parslow et al. (2003a),(2003b), but draws on the additional sediment data collected during the present study to improve model initialisation

Nutrient cycling

The biogeochemical model component of EMS used for this project was similar to that used by Parslow et al. (2003a),(2003b), but the model was recalibrated and validated using the extended data set available through the current project (using 2002-2003 data for calibration and 2004-2006 data for validation). A salinity limitation function was introduced for growth of freshwater phytoplankton to reflect observed conditions.

Nitrogen is used as the primary currency of the model; i.e. most model components including dissolved forms, algae and aquatic plants are represented in terms of how much nitrogen they contain, and most processes convert nitrogen from one form to another. Phosphorus, carbon and oxygen are included as secondary currencies which can also affect process rates such as growth of algae.

Most of the processes and algorithms used in the model are as described by Murray and Parslow (1997), who describe the Port Phillip Bay model, a predecessor of EMS.

The model's performance was compared with a full spectrum of observed nutrient and sediment concentrations, as well as salinity and temperature (see Section 6.5.1).

This model suite is hereafter referred to as "the biogeochemistry model", or EMS.

6.1.2. The ecological model

A preliminary foodweb model was also developed for this part of the river. The model, built with Ecopath and Ecosim (Christensen and Walters, 2004; Christensen et al., 2005), is based on food web ecology using mass-balance methods originally derived by Polovina (1984) and includes ecosystem flow analysis tools and ecosystem theory developed from Baird and Ulanowicz (1993) and Christian et al. (2005).

The model simulates the flow of biomass through 55 compartments that represent a variety of animals such as barramundi and other fish species, crocodiles and water birds, plants, algae, bacteria, nutrients and detritus.

Because the available ecological data were patchy, many assumptions needed to be made in developing the model, and in application to management scenarios, the results should be considered speculative. The model has considerable potential to be enhanced by targeted data collection, and extended to include zones further downstream to permit exploration of alternative management scenarios.

The foodweb model and its application to the freshwater zone of the Ord River are described in detail in the Ecological Synthesis Report Gehrke, P. (2008).

6.2. Description of scenarios

6.2.1. Inflows

In consultation with local stakeholders and the W.A. Department of Water, a series of scenarios have been developed to reflect likely changes to water allocation and the management of the Ord River over the next few years. These scenarios were:

1. Current hydroelectric power production (a limit of 210 GWh per year) and current irrigation arrangements (the stage 1 irrigation area).
2. Increased dry season flows associated with an increase in hydroelectric power production (to 327 GWh), and current irrigation arrangements.
3. Increased hydroelectric power generation combined with the implementation of the M2 irrigation scheme (an additional irrigation area, provided by water extracted from the Kununurra Diversion Dam, with no additional irrigation return flows).

4. Current power generation and irrigation areas, with a 50% reduction in irrigation return flows (the volume of water flowing back into the Ord River after traversing irrigated farmland).
5. Current power generation and irrigation areas, with a 100% reduction in irrigation return flows. Although not likely to occur, running this scenario allowed us to explore the impact of irrigation return flows, and the maximum range within which improvements to the management of these flows might influence conditions in the river.
6. A comparison of the new (current) environmental water provisions (EWPs) with the interim EWPs that these provisions superseded Braimbridge, M. and Malseed, B. (2007).

Because the impact of each of these management scenarios is likely to vary from one year to the next, depending on climatic conditions, a number of sub-scenarios were conducted for each management scenario. These sub-scenarios represented flows likely to occur during a wet year, a typical year, a dry year, and a sustained drought with severe water restrictions.

For the wet year scenarios, inflows were based on flows expected if climatic conditions matched those observed in 1913-1914, a particular wet year in history. For the typical year, flows were based on estimated flows in a year with rainfall corresponding to those of 1950-51. For the dry year, 1932-33 was used as the reference, and for the drought scenarios, we used 1932-34. For each case, the Department of Water provided simulated daily flows from Kununurra Diversion Dam, Dunham River, and the irrigation drains, for input to our models. These flows are described in more detail in Appendix 3. Flows used for scenario 1 are plotted in Figure 15: flows for other scenarios are variations upon these.

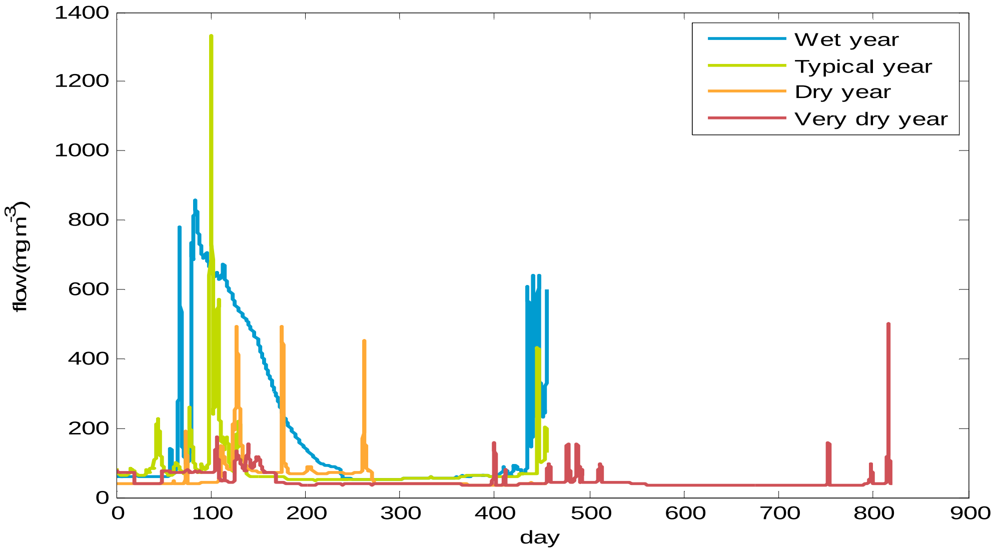

Figure 15 Daily flows at Tarrara Bar, combining the tributary flows specified for scenario 1 (current conditions)

6.2.2. Sediment and nutrient loads

Monthly water quality observations are not sufficient to adequately define day-to-day changes in sediment, nitrogen and phosphorus loads from tributaries to the lower Ord River. Sediment and nutrient concentrations associated with flows can vary rapidly, particularly when flows change rapidly in response to rainfall.

Unfortunately, these responses can be difficult to capture as rainfall events are unpredictable and larger flood events in particular make sampling difficult in this remote location. Hence, it was necessary to make some assumptions about how sediment and nutrient concentrations change as a function of flow.

Examining the available data, no correlation was found between concentrations of dissolved organic or dissolved inorganic nitrogen and phosphorus, and flow. Hence, it was assumed for these scenarios that dissolved nutrient concentrations in each tributary would remain constant (at the mean observed concentration) regardless of flow.

Correlations of particulate nutrient and total suspended sediment concentrations with flow from Kununurra Diversion Dam or the irrigation drains were weak. Concentrations of particulate nitrogen (PN), particulate phosphorus (PP), and total suspended sediments (TSS) in the Dunham River, however, correlated reasonably well with flow from the River. Counter-intuitively, concentrations of these components in the irrigation drains (D2, D4 and D6) and downstream of Kununurra Diversion Dam (at Ivanhoe Crossing, OIVANX, where available, otherwise the nearest downstream site – usually Tarrara Bar, OTARB in Figure 2) also correlated moderately well with flows from the Dunham River, probably because factors such as local rainfall that contributed to flow in the Dunham River also caused surface runoff to the drains.

Particulate nitrogen and phosphorus concentrations and TSS concentrations in all tributaries were thus specified for each scenario as functions of flow in the Dunham River. The goodness of fit – an indication of the accuracy of this method of estimating loads - varied, ranging from a low of $r^2 = 0.13$ for the correlation between Dunham River flow and TSS in D2 to a high of $r^2 = 0.74$ for the correlation between Dunham River flow and TSS downstream of Kununurra Diversion Dam[15]. Any improvement in the data available to specify these relationships would improve the accuracy of the model and our confidence in model predictions.

6.2.3. Application of models to scenarios

The biogeochemistry model was run using the flows, nutrient and sediment loads, developed for each scenario. Scenarios were then compared and evaluated in terms of their impact on simulated water quality and primary production (growth of plants, in this context represented by algae).

These results for “typical year” flow conditions were used as input for the foodweb model in a steady-state mode to provide a basis for speculation about the possible impacts of these changes on fish and other higher-level ecology.

6.3. Scenario results: biogeochemistry

The biogeochemistry model results for each scenario (2-6) were compared with the scenario representing current conditions (scenario 1) in terms of simulated total and dissolved nutrient concentrations, chlorophyll *a*, concentrations of benthic microalgae, concentrations of total suspended solids, and net water column and benthic primary production. In evaluating these results, we took the benthic microalgae group to represent the responses of both microalgae growing on the bottom and sides of the river channel, and epiphytic algae growing on the surfaces of larger plants such as ribbonweed.

Model outputs were considered both spatially and temporally. All of the scenarios considered a significant change in dry-season flow or nutrient loads, which had a smaller impact on wet-season flows and loads. Accordingly, all of the scenarios showed a greater impact on dry season conditions than wet-season conditions, except for the very dry year, for which most changes were small (see e.g. Figure 16).

The clearest changes in all of the scenarios occurred in the freshwater zone, where nutrient concentrations are controlled primarily by day-to-day nutrient loads and flows rather than

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[15] r^2 for particulate phosphorus (PP) in D4: 0.56973 (22 degrees of freedom); for PP in D2: 0.22 (df=21); for PP in Dunham River: 0.65 (df=32); for PP downstream of Kununurra Diversion Dam: 0.71 (df=32). r^2 for TSS in D4: 0.21 (df=22); for TSS in D2: 0.13 (df=21); for TSS in Dunham River: 0.69 (df=32); for TSS downstream of Kununurra Diversion dam: 0.74 (df=32). r^2 for particulate nitrogen (PN) in D4: 0.15 (df=22); for PN in D2: 0.19 (df=21); for PN in Dunham River: 0.26 (df=32); for PN downstream of Kununurra Diversion Dam: 0.30 (df=32).

interactions with sediment stores, and where primary production is most responsive to changes in nutrient concentrations due to high water clarity.

In the estuary, responses are mediated by the effect of changes in flows on sediment stores and sediment resuspension, and hence are more difficult to interpret. These changes may take longer to show their full effect than the one-and-a-half-year time-frame considered here.

Scenario 6 – the interim EWP regime – made very little difference except for a slight worsening of water quality in dry years in comparison with the current EWP. This scenario is not discussed further here.

Results for the freshwater zone for scenarios 2 to 5 are summarised in Table 1 and detailed as percentage changes in average concentrations or production rates, in Table 2. As a generalisation, increases in nutrient and chlorophyll concentrations represent a change for the worse, while reductions in nutrient concentrations and increases in benthic primary production are probably changes for the better. There is some evidence that epiphytic algae are an important component of the foodweb, and (within limits), increases in production are likely to feed into increased fish production.

In general, scenarios 4 and 5 (reductions in irrigation return flow and the associated nutrient and sediment load) resulted in improved water quality and increased primary production due to more light reaching the river bed. The difference between scenario 4 (a 50% reduction in irrigation return flows) and scenario 5 (a 100% reduction) was one of degree, with a greater improvement apparent in scenario 5.

Results for scenario 2 (increased hydroelectric discharge) are equivocal, showing increased benthic primary production and reduced phytoplankton production in dry years, and the reverse in the wet-year scenario. Overall, the impact of this change on water quality in the Ord River is likely to be minor, although the effect on higher-level ecology might be greater (section 6.4).

Results for scenario 3 (increased hydroelectric generation combined with increased extraction to irrigate the M2 area) are also mixed, showing reduced water column and benthic production in some circumstances, and reduced inorganic nutrient concentrations, but increased total phosphorus and chlorophyll *a*.

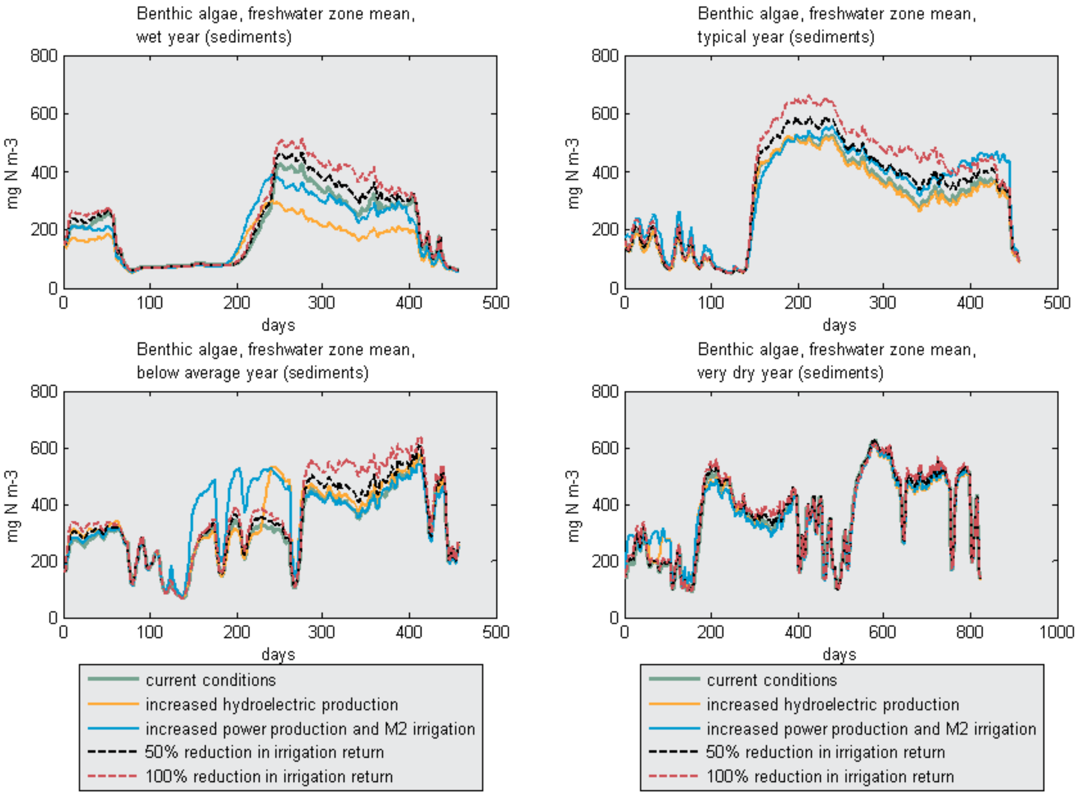

Figure 16 Example time-series for scenario results, showing daily variations in concentrations of benthic algae, averaged spatially over the freshwater zone. The x-axis in each case shows time in days from the start of the simulation.

Table 1 Summary of scenario results for the freshwater zone

	Increased hydroelectric discharge (scenario 2)	Increased irrigation with increased hydroelectric discharge (scenario 3)	50% or 100% reduction in irrigation return flows (scenarios 4 and 5)
Wet year	• Increased phytoplankton production • Reduced benthic production • Higher nutrient concentrations	• Reduced benthic production • Lower chlorophyll concentrations	• Reduced nutrient concentrations • Increased benthic primary production • Reduced phytoplankton production
Typical year		• Increased benthic production • Higher chlorophyll concentrations • Lower DIN but higher TP concentrations	• Reduced nutrient concentrations • Increased benthic primary production • Reduced phytoplankton production
Below average year	• Reduced phytoplankton production • Increased benthic production	• Increased benthic production • Higher chlorophyll concentrations • Lower DIN but higher TP	• Reduced nutrient concentrations • Increased benthic primary production • Reduced phytoplankton

	• Lower DIN concentrations	concentrations	production
Very dry year		• Lower DIN concentrations	• Reduced nutrient concentrations • Increased benthic primary production • Reduced phytoplankton production

Table 2 Percentage change (from current conditions) in simulated conditions in the freshwater zone for four scenarios.

	increased hydroelectric discharge	increased hydroelectric discharge and M2 irrigation	50% reduction in irrigation return flows	100% reduction in irrigation return flows
net water column oxygen production				
Wet year	0%	3%	-7%	-15%
Typical year	1%	-9%	-8%	-17%
Below average year	-6%	-3%	-6%	-13%
Very dry year	-2%	-3%	-5%	-12%
net benthic oxygen production				
Wet year	-66%	-20%	20%	46%
Typical year	-6%	30%	18%	42%
Below average year	7%	1%	11%	25%
Very dry year	-9%	-11%	3%	6%
chlorophyll a				
Wet year	-30%	-8%	2%	3%
Typical year	-3%	17%	2%	3%
Below average year	5%	18%	-2%	-5%
Very dry year	3%	4%	-2%	-6%
benthic algae				
Wet year	-24%	-6%	8%	17%
Typical year	-3%	14%	8%	19%
Below average year	7%	12%	5%	11%
Very dry year	0%	-1%	2%	4%
total nitrogen				
Wet year	-2%	-1%	-2%	-5%
Typical year	0%	0%	-5%	-9%
Below average year	-2%	-2%	-3%	-7%
Very dry year	-2%	-4%	-5%	-10%
total phosphorus				
Wet year	-2%	-1%	-2%	-4%
Typical year	0%	2%	-3%	-6%
Below average year	-1%	-1%	-3%	-6%
Very dry year	-1%	-2%	-2%	-4%
dissolved inorganic nitrogen				
Wet year	11%	4%	-6%	-12%
Typical year	1%	-10%	-12%	-23%
Below average year	-8%	-11%	-7%	-13%
Very dry year	-5%	-9%	-13%	-24%
dissolved inorganic phosphorus				

	increased hydroelectric discharge	increased hydroelectric discharge and M2 irrigation	50% reduction in irrigation return flows	100% reduction in irrigation return flows
Wet year	8%	2%	-6%	-12%
Typical year	1%	-5%	-8%	-16%
Below average year	-7%	-11%	-7%	-13%
Very dry year	-4%	-5%	-4%	-6%

6.4. Consequences for fish and other animals

The predicted changes in detritus, benthic microalgae and chlorophyll *a* were used as input to the foodweb model in static mode (i.e. changes over time were not considered, only overall average changes). As the foodweb model has not been validated against detailed field observations, the following results suggest plausible ecological responses, but cannot be considered firm predictions.

Scenario 2 – Increased hydroelectric discharge – is expected to cause a small decrease in overall production. This might mean fewer barramundi and other fish because there is less food in the freshwater zone.

Scenario 3 – Increased hydroelectric flow and M2 irrigation – results in a relatively large increase in primary production, which in time, is expected to translate into increased production at higher trophic levels. This might mean increased fish populations, although changes in habitat associated with changed water levels might alter which species dominate.

Scenario 4 – 50% reduction in irrigation return flows – results in a moderate increase in primary production, which in time, is expected to translate into moderate increases in production at higher trophic levels. This means more fish, but fewer than in Scenarios 3 or 5.

Scenario 5 – 100% reduction in irrigation return flows – results in a relatively large increase in primary production, which in time, is expected to translate into increased production at higher trophic levels. This means more fish.

6.5. Limitations

6.5.1. Accuracy of model predictions

A model is by definition a simplified approximation of reality, and model predictions are always subject to error and uncertainty. Sources of error include errors and uncertainty in inputs (for example, uncertainty in sediment and nutrient loads for the management scenarios, discussed in part in section 6.2.2), simplifications and assumptions in the way processes in the model are represented, the impact of processes that are not included in the model (for example, pumping of water through intertidal mudflat sediments), and errors in model parameterisation (for example, the rate at which algae grow given ample light and nutrients). Model predictions must therefore be used with caution, although they do represent our best educated guess as to how the system will respond to changes.

One method of estimating how accurate the model predictions will be is to look at how well the model performs when used to reproduce existing conditions. For this study, the biogeochemistry model was developed and calibrated using observations from 2002-2003, and can be evaluated by examining its performance in reproducing observed conditions in 2004-2006. This performance should be considered both in terms of spatial and temporal accuracy (i.e. the accuracy of the model in predicting how concentrations vary along the length of the river and estuary, and the accuracy of the model in predicting how concentrations at one site vary over time).

Detailed, month-by-month comparisons have been made for each variable included in the model for which observational data were available. Examples are shown in Figure 17. In general, the model reproduces observed patterns in the spatial distribution of nutrients, suspended sediments and oxygen reasonably well, and reproduces observed spatial patterns in salinity very well.

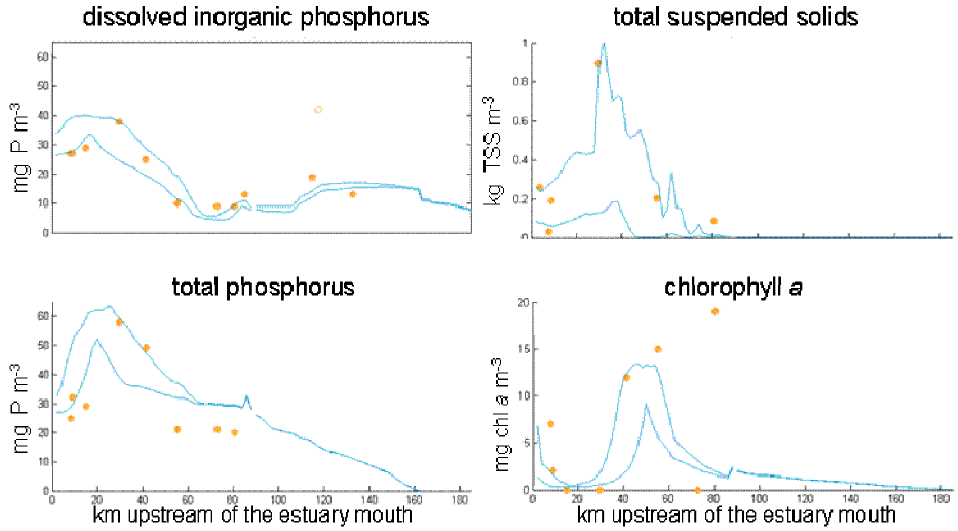

Figure 17 Example spatial comparison of model predictions (blue lines) with water quality observations (orange dots). The hollow dot (top left plot) indicates a sampling site immediately downstream of a minor tributary creek draining into the Ord River, which is not included in the model. Upper and lower lines indicate the minimum and maximum simulated concentration from three-hourly model output over a full tidal cycle on the day the water quality samples were taken. Concentrations of suspended sediments vary by orders of magnitude over the course of the tidal cycle in the high-energy estuarine zone. The break in the blue lines indicates the break between the freshwater zone of the river and the tidal zones.

The model is less accurate in reproducing observed temporal variations (Table 3). This is in part due to the enormous variations that occur in sediment and nutrient concentrations in the estuary over the course of each tidal cycle (figures are based on 3-hourly model output, and concentrations in the estuary can vary enormously over this period), and in part to the limited temporal resolution of inflow nutrient concentrations.

Table 3 Coefficient of determination (r^2) and relative error (RE) for temporal variation in several water quality components at three sites in the estuary, 2002-2003. Upstream boundary conditions predicted from flow. Site locations are shown in Figure 2.

	OSPW (estuary mouth)		OROCK (high-energy estuarine zone)		OMATIS (freshwater tidal zone)		OTARB (freshwater zone)	
component	**r^2**	**RE**	**r^2**	**RE**	**r^2**	**RE**	**r^2**	**RE**
temperature	0.97	1.5%	0.90	3.7%	0.91	3.7%	0.64	7.8%
total suspended solids	0.20	116%	0.66	104%	0.55	65%	0.65	67%
Total nitrogen	0.37	63%	0.02	45%	0.01	48%	0.15	176%
dissolved oxygen	0.70	8.8%	0.49	4.8%	0.50	6.9%	0.19	7.9%
dissolved inorganic phosphorus	0.25	35%	0.01	47%	0.14	27%	0.08	30%
dissolved inorganic nitrogen	0.27	62%	0.04	81%	0.01	102%	0.08	74%
chlorophyll *a*	0.60	74%	0.21	187%	0.37	51%	not calculated: insufficient observational data	

In summary, we believe that the numerical models capture the most important physical and biochemical processes that affect nitrogen, phosphorus, sediments and growth of algae in the lower Ord River and estuary. Scenario predictions for water quality and primary production are likely to be accurate insofar as they indicate a general direction of change and perhaps the relative magnitude of change, but should not be taken as predictions of concentrations at any given time, or the exact degree of change expected for any given scenario.

The ecological model has not been validated against field data, although it does illustrate a system that behaves in accordance with what is known about the ecology of the lower Ord River. More information is needed to improve and validate the model so that it can be used in a predictive mode.

6.5.2. What is not included in the model

It is not possible to include everything in a model, however a few omissions in particular stand out as potentially important. These are discussed below.

1. Floodplain interactions.

During large floods, the Ord River spills out over a sizeable area of floodplain. The one-dimensional models developed during this project do not consider the floodplains, and even for the “wet year” scenarios, water is assumed to be constrained to the river channel, which is unlikely for such large flows. During floods, sediment and particulate nutrients are likely to be deposited onto the plain (but nutrients may also be picked up from flooded areas), and habitats not normally part of the river become connected to it. The effects of these interactions on conditions in the lower Ord River in the aftermath of a flood are not known.

To model floodplain interactions would require a digital elevation model (i.e. detailed topological information) for the floodplain, as well as sampling of floodplain soils and additional, targeted process studies.

2. Macrophytes (plants)

Concurrent with the study reported here, a study of vegetation in and around the freshwater zone has recently been completed. The impacts of plants on flow, sediment and nutrient dynamics and the impacts of flow and nutrients on vegetation, have not been considered in this study, but now that both studies are complete, there is the potential to combine them and attempt to model plants and habitats in the lower Ord River.

3. Vertical oxygen dynamics in deeper pools in the freshwater zone.

None of the scenarios resulted in significant changes in oxygen concentrations, although all scenarios resulted in some change in net oxygen production. This is because of the impact of exchanges with the atmosphere. One-dimensional models were chosen for this study because water in most of the Ord River is vertically well-mixed[16], however there may be times when deeper pools of the freshwater zone (particularly Carlton Crossing pool) become temporarily stratified Trayler, K. et al. (2003a), and our one-dimensional model is not capable of representing the potential for oxygen depletion at depth in these conditions. Previous work Trayler, K. et al. (2003b) suggests that oxygen-depleted conditions in the lower Ord River are unlikely.

4. Intertidal mudflats: wetting and drying, pore-water exchanges.

Although the use of a one-dimensional model allowed the exploration of a large number of scenarios, this choice limited our ability to explore the three-dimensional processes that occur on intertidal mudflats. In particular, the impact of mudflat pore-water exchanges with estuary water over the tidal cycle are not known.

5. Tidal creeks.

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[16] Measured differences between surface and bottom temperature were generally less than 0.1°C at most sites.

Preliminary modelling of the tidal creeks suggest that this zone has only a small impact on nutrient cycling in the estuary, however the tidal creeks have not been included in regular monitoring for logistical reasons, and have not been included in the main hydrodynamic and biogeochemistry models discussed in this report.

6. Foodweb interactions in the estuary and interactions between marine, estuarine, and river habitats.

Although sufficient ecological data were available for the freshwater zone to allow the construction of a preliminary foodweb model, ecological data for the other zones described in Section 3 are very limited, so it has not been possible to extend the foodweb model into these zones, nor to simulate the ecological interactions between these zones.

7. Impact of habitat changes on ecology.

The ecological model discussed in 6.1.2 and described in the Ecological Synthesis Report Gehrke, P. (2008) considers foodweb interactions, but does not consider the effect of changes in habitat (e.g. changes in water level or salinity) on the ecosystem.

8. Impact of ecological changes on water quality

The biogeochemistry model behaves as an open system, with nutrients coming in from the catchment and flowing out to the ocean, but between these points, cycling among detritus, dissolved forms, algae and *zooplankton*, and to some extent exchanged with sediments and the atmosphere. Transfer of nutrients up the food chain is not incorporated into this system (though it is considered separately by the foodweb model) and can in some instances have an important impact on water quality Hunt, R.J. et al. (2003) however increasing the complexity of aquatic models beyond a certain point is not desirable, because the more intensive data requirements of more complex models do not necessarily produce better or more reasonable results (Walters and Martell, 2004) and has been shown in many cases to reduce the accuracy of predictions (Fulton, E.A. et al. (2003).

6.5.3. Potential future scenarios not considered

The scenarios considered in this report were chosen because they are both likely, in terms of management of the Ord in the near future (with the exception of the 100% reduction in irrigation return flows) and tractable in modelling terms. A range of other future scenarios are not only possible but likely. Two of these possibilities deserve special mention.

First, there is currently a proposal under consideration to build a tidal power plant in the estuary. This would extract a great deal of the tidal energy that drives the system, and would constitute a very large change to the physical and biological dynamics of the lower Ord River. The conceptual models of the estuary presented in Section 3 would no longer apply. The hydrodynamic and biogeochemistry models here, or similar models, could potentially be adapted to explore one component of the problem.

Second, long-term climatic change will inevitably influence the way the system functions. To predict the impacts of climate change on the Ord River would require a much larger study, incorporating regional climate models with catchment models, models of the river like those presented here, and predicted changes in water level and tides. Additional process studies to explore the impact of changes in temperature and carbon dioxide concentrations on specific processes should also be included in any such study.

RECOMMENDATIONS FOR FURTHER RESEARCH

There is a need for further research to fill the knowledge gaps that have been identified during this study. Chief among these is the lack of ecological data for the estuary downstream of Carlton Crossing. Ecological knowledge gaps are discussed in more detail in the Ecological Synthesis Report Gehrke, P. (2008).

This study has focused on processes within main channel of the river and estuary. Interactions between the river and its floodplain, between the estuary and tidal creeks, between the estuarine channel and its mudflats, and between the main arm of the estuary and the west arm are all in need of further study. The role of the floodplains during flood events may be particularly significant, as this can affect sediment and nutrient loads retained within the estuary as well as fish recruitment and other ecological links.

One relatively simple step that would improve the predictive capacity of the biogeochemistry model would be to gather more data to characterise the relationships between flow, nutrient and sediment loads from Kununurra Diversion Dam, Dunham River, and the irrigation drains. This would require frequent (daily or better) sampling over the duration of several rainfall events over the course of at least one wet season. Additionally, catchment modelling might provide improved estimates of loads associated with flows to the lower river.

Finally, as discussed in 6.5.3, this report has not considered the possible impacts of other management and development options, nor the likely impacts of climate change on the lower Ord River and Estuary. These may ultimately result in changes that outweigh any of those considered here.

APPENDIX 1: MONITORING METHODS AND SITES

The field program consisted of two parts: a monthly estuary monitoring program, and wet and dry season campaigns. The monthly water quality monitoring program was developed and implemented in collaboration with WA Department of Water (DoW) in Kununurra, and led by a DoW officer Duncan Palmer. The monitoring program was designed to provide basic information on water and sediment quality, on physical exchanges and the cycling of nutrients, and on the sources and sinks of organic matter in the water and sediments on the lower river and estuary.

Water samples were collected at 0.5 metres depth from 8 sites in the Ord estuary (Table 1.1, Fig. 1.1). Hydrolab surface and bottom readings of Temperature, Salinity, Dissolved Oxygen and turbidity were obtained at these 8 sites plus an additional three sites in the estuary, with one site (Mambi Is) measured at start and finish of sampling run. (Table 1.1, Fig. 1.1). The estuary monitoring was designed to complement existing ongoing monitoring undertaken by WRC in the lower Ord river and irrigation area. Estuarine samples were conducted at approximately 4 weekly intervals, generally adjacent to river sampling. Estuarine sample collection was intended to commence at the lowest point on the river (Scott Point) on or near high tide on a neap tide cycle. Secchi depth measurements were collected at each site.

Two 1 L samples were collected at each water sampling site and stored in coolers on ice in the field, and then at 4°C, until shipped, usually within 24 hrs of collection, from Kununurra to Perth. Samples were analysed by the National Measurement Institute (NMI) laboratory in Perth for TN, TP, Chloride Ion, Salinity, TSS, Nox, NH3, SiO2, Alk, FRP, DON, DOP, DOC, Chlorophyll-a.

All sampling sites were registered in the DoW “WIN” database. Field log sheets were kept in the Kununurra Office, and log sheet information entered into the database. Hydrolab measurements were electronically stored in Kununurra, with a copy sent to CSIRO Marine Research. Hydrolab data were also entered into the “WIN” database. Water sample data received from the NMI laboratory were entered into the “WIN” database, stored locally in Kununurra and a copy provided to CSIRO.

Table 4 Estuarine sample sites

Site Code	Site Description	Easting*	Northing*	Water Sample	Hydrolab
SPW	Scott Point West	0413155	8319686	Yes	Yes
SPE	Scott Point East	0414879	8319646	Yes	Yes
PI	Panton Island	0416436	8314731	Yes	Yes
FI	Fossil Island	0417000	8308203	No	Yes
FIUS	Fossil Island upstream	0423761	8302422	Yes	Yes
GI	Green Island upstream	TBD	TBD	Yes	Yes
BLITZ	Blitz Ck	0427756	8286674	No	Yes
ROCKS	The Rocks	0429837	8287328	Yes	Yes
COLUS	Upstream of Collins Ck	0432329	8284617	No	
MATIS	Mattress Is	0438471	8283959	Yes	Yes
MAMIS	Mambi Is	0439512	8279122	Yes	Yes x2

*Datum AMG Zone 52

APPENDIX 2: BIOGEOCHEMICAL STUDIES: METHODS AND AIMS

The principal aims for the biogeochemical studies can be summarised as follows:

1. To identify the major sources of organic matter to Ord sediments
2. Investigate which sources might be important with respect to higher trophic levels
3. Contribute to a general understanding of the relative importance of benthic vs pelagic production
4. Investigate algal-bacterial interactions (ie which OM pool is most labile)

Techniques used for each question:

1. Bulk stable isotopes and lipid markers
2. Bulk and marker specific stable isotopes
3. Bulk and marker specific stable isotopes, lipid markers, pigments
4. Marker specific stable isotopes

Brief description of techniques:

Lipid markers

Organic matter contains a wide range of chemical compounds which can be analysed by a variety of techniques. Particular groups of these compounds often have very different abundances depending on the source of that organic matter and even more importantly some compounds will only occur when certain sources (for example algae vs terrestrial plants) have contributed to the organic matter pool. As biogeochemists we can use this information to assess the relative importance of different sources.

An added aid to this assessment is the isotopic signature of the material. Carbon and nitrogen predominantly occur in one stable form (known as carbon-12 and nitrogen-14). However, they both also occur in another much less common stable form, carbon-13 and nitrogen-15. the Relative amounts of the two stable form for each element is different in different plants and animals depending on where they get their carbon and nitrogen from. By using sensitive equipment we can measure these ratios and use the information to make an assessment of different sources of organic matter.

For a more sensitive analysis we can combine the above two techniques and measure the isotopic ratios for individual marker compounds. This can be particularly powerful where a particular marker can have different sources or in using specific markers from bacteria to determine which types of organic matter are more readily degraded.

Results summary for each question:

1. Ord river sediments are in general very low in organic matter when compared with temperate estuaries. The organic matter that is present is dominated by material of terrestrial origin. It has to be remembered that we are measuring what is left behind and in a system with very low carbon, all the “good” carbon is likely to be utilised very rapidly.

2. Stable isotope investigations strongly suggest higher trophic levels rely predominantly on algal production. Low rates of primary production mean that there is little opportunity for this material to be recorded in the sediments. Lipid and pigment markers however indicate the presence of small quantities of algal carbon. This again suggests that algal carbon is being consumed at the same rate as it is being produced. The dominance of terrestrial material in the system merely reflects its

recalcitrant nature but could be misconstrued as representing an (overestimated) importance to the system.

3. The relative role of benthic algae is hard to determine at this time, primarily due to a high degree of spatial variability. It's not completely understood what controls this variability but water clarity, flow and sediment type can be expected to play important roles. Between the two field surveys some freshwater sites showed a significant increase in benthic algal markers, which appears to be a response to a prolonged period of low flow and increased water clarity. Towards the mouth the situation is more complicated with suitable substrate frequently appearing and disappearing (eg mud islands).

4. Detailed process investigations appear to show a tight relationship between bacterial abundance and algal material. There is good evidence that the bacteria are consuming particular algal products, indicating that algal carbon is the most labile (and therefore most important) within the system.

APPENDIX 3: DETAILED DESCRIPTIONS OF SCENARIO FLOWS BY IAN LOH, DEPARTMENT OF WATER

Water year 1913-14- Wet conditions

Starting water levels in Lake Argyle and inflows to the Ord River Dam during the wet season of 1913-14 are well above average (~ 90th percentile). As a result, flows in the lower Ord River are dominated by spillage from Lake Argyle until May. For the remainder of the dry season flows are dominated by surplus releases made for Hydro-power generation. These flows are in excess of the normal dry season environmental water provision of 42 m^3/sec. Note the higher flows for the No M2 -327 GWh case, relative to the M2=400 – 327 GWh and No M2 -210 GWh cases and reflects the higher power station releases and current irrigation demand for this case. Most irrigation demand is diverted upstream of the Kununurra Diversion Dam. Drainage returns from the Stage 1 irrigation areas occur downstream. (The new M2 Area will drain to the Keep River and away from the lower Ord). Under current irrigation practice and this wet year, drainage returns are about 4% of the total dry season flow. However, the nutrient loads of return flows are a much higher percentage of the total nutrient load.

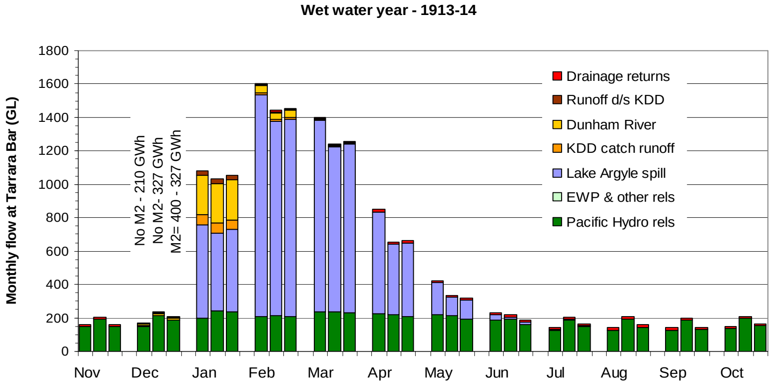

Figure 18 Contributions to flows in the lower Ord River for the "wet year" scenarios

Water year 1950-51 – Typical year

Starting water levels in Lake Argyle and inflows to the Ord River Dam during 1950-51 are close to long term median values. No spillage occurs from Lake Argyle. Flows in the lower Ord during the wet season are primarily from the Dunham River and the catchment between the two dams (the KDD catchment), with the base flow component coming from Hydro power releases. During the dry season, runoff from the unregulated catchments cease and lower Ord flows reduce to the surplus of hydro-power releases. Note differences occur in dry season flows between scenarios, reflecting the different power and irrigation demands. Flows are usually 5 -10 m^3/sec greater than the dry season EWP (42 m^3/sec) for the No M2 -210 GWh and No M2 -327 GWh cases, and are maintained at the EWP in the M2=400 – 327 GWh case. Under current practice, drainage returns are ~ 9% of the dry season flow in this typical year.

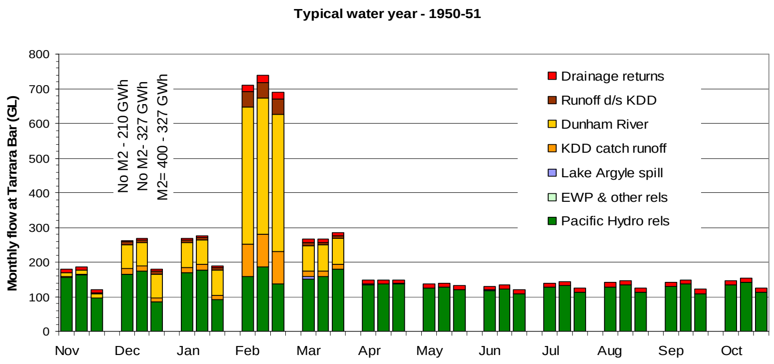

Figure 19 Contributions to flows in the lower Ord River for the "typical year" scenarios

Water year 1954-55 – Mild irrigation restrictions

Starting levels in Lake Argyle are very low (77 m to 75 m depending on the scenario) and the inflow is well below average (~ 28th percentile). Releases for power generation are possible from February to July under the No M2 -210 GWh case as Lake Argyle is marginally higher (by 1 to 2 m) and power generation restrictions less severe; a result of the lower combined demand of this case. Note that flows for the remainder of the year are dominated by releases made to meet the lower Ord environmental water provisions (and irrigation demand). Environmental flows are restricted to 37 m^3/sec for most of the year. Restrictions also applied to the irrigation demand. These varied between cases and seasons. For the No M2 -210 GWh case, 100% of demand was supplied prior to 1st April 1955 but was restricted to 75% of demand after 1st April. For the No M2 -327 GWh and M2=400 – 327 GWh cases, irrigation supply was restricted to 81% and 90% of demand respectively before 1st April and to 55% and 69% respectively after 1st April. "Mild' restrictions and current practice result in drainage returns varying from 4 to 7 % of dry season flows.

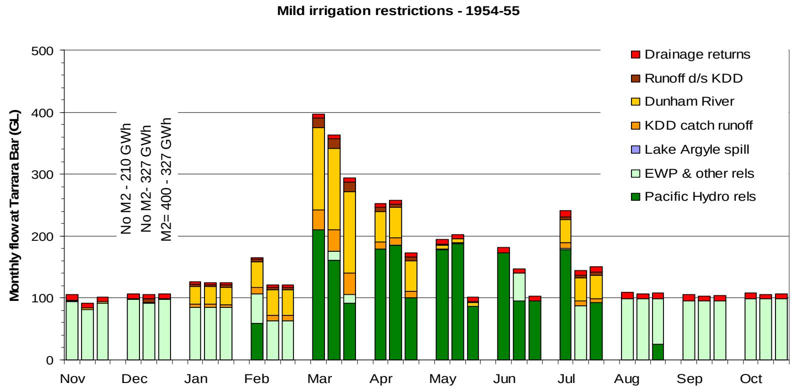

Figure 20 Contributions to flows in the lower Ord River for the "dry year" scenarios

Water year 1932-33 – Severe water restrictions

Starting levels in Lake Argyle are very low (~ 78 m to 77 m depending on the scenario) and inflows are very low (10th percentile). Restrictions to the environmental provisions, irrigation and hydro-power demand all occur during the year. The environmental water provisions are reduced to 37 m^3/sec for most of the year, and reduce further to 32 m^3/sec for ~10 days of the year. Flows in the lower Ord during the dry season are dominated by releases made to maintain these provisions. Some additional power generation releases are made during the wet season, especially for the No M2 -210 GWh case (as water levels are marginally higher). From April 1933, irrigation diversions are restricted to 43%. 40% and 39% of demand for the No M2 -210 GWh, No M2 -327 GWh case and M2=400 – 327 GWh cases respectively. Drainage returns under severe restrictions and current irrigation practice represent from 4 to 5% of dry season flows.

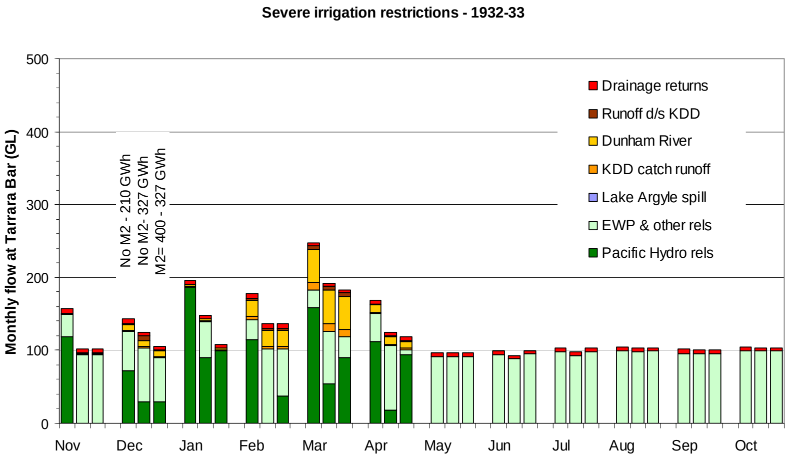

Figure 21 Contributions to flows in the lower Ord River for the “drought” scenarios

Water year 1933-34 – Severe water restrictions

Starting levels in Lake Argyle are the second lowest simulated (~73 m to 71 m depending on the scenario). Inflows to the Ord Dam are very low (16th percentile), although not as severe as 1932-33. Flows on the lower Ord are very similar between scenarios. The only releases being made from Lake Argyle are to supply the (restricted) irrigation demand (diverted at Lake Kununurra), and to meet the restricted EWP of 32 m^3/sec. During the wet season months (minor) unregulated flows from the Dunham River and KDD catchment also contribute. Diversions for irrigation are restricted throughout the year to 27%, 26% and 22% of demand for the No M2 -210 GWh, No M2 -327 GWh case and M2=400 - 327 GWh cases respectively. Under current irrigation practice and these most severe restrictions, drainage returns represent from 3% to 3.5% of dry season flows.

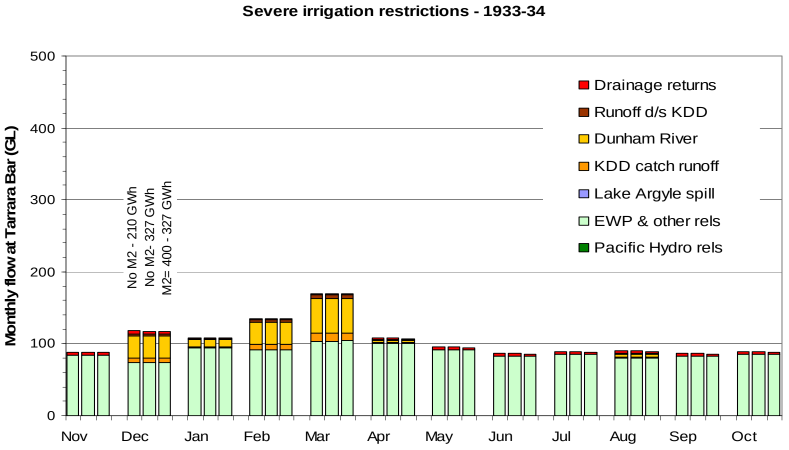

Figure 22 Contributions to flows in the lower Ord River for the Wet year scenarios

GLOSSARY

benthic: Relating to the bottom of the river. Benthic algae are algae growing on the river-bed.

bioavailable: Available for uptake by animals or plants. Bioavailable nutrients are those that can be readily absorbed by algae and other plants.

biomass: The mass of biological material in plant and animal populations.

biogeochemistry: The study of the cyclical exchange of elements between living and non-living components of an ecosystem (e.g. cycling of nitrogen from detritus by bacterial decay to dissolved inorganic nitrogen, and of dissolved inorganic nitrogen by uptake from the water to plants).

brackish: Having a salinity that is too high for drinking water, but appreciably fresher than sea water. Although various classification schemes have been developed that assign the term “brackish” to specific salinity ranges, these ranges are not consistent and the term is vaguely defined in general usage.

catchment: The area of land that contributes water to a river, either through surface runoff after rain, or subsurface flow.

conceptual model: A description in words or pictures of how we believe a system – in this case, the lower Ord River - works.

detritus: Decaying organic matter, such as dead leaves and dead algae.

dissolved nutrients: Nutrients in dissolved forms, such as ammonia and ionic nitrate and phosphate.

ebb tide: The tide when it is “going out”, i.e. water levels falling. The opposite of a flood tide.

epiphyte: A plant growing on the surface of another plant. In the context of this report, algae growing on the leaves and stems of larger plants.

estuary: The section of the river influenced by tides and sea water, i.e. from Carlton Crossing downstream to the mouth of the river at Cambridge Gulf.

EWP: Environmental Water Provisions.

flood tide: The tide “coming in”, i.e. water levels rising. The opposite of an ebb tide.

hydrodynamics: The study of flows and mixing of water.

lower river: The section of the Ord River downstream of Kununurra Diversion Dam but upstream of Carlton Crossing.

neap tide: Tidal height ranges typically cycle over a 2-week period. Neap tides refer to the time within this cycle when the tidal range is relatively small. The opposite of a spring tide.

numerical model: A mathematical model, usually a computer model that simulates how a system (such as the lower Ord River) behaves. Numerical models can be used to test our understanding of a system, explore the interactions of different parts of the system, and predict how the system might behave in future.

nutrients: In this report, the term “nutrients” is used to refer to **nitrogen** and **phosphorus**, two elements essential to growth of plants and algae. Nitrogen and phosphorus loads to a river tend to increase with catchment development, and in rural areas, this increase in nitrogen and phosphorus loads is often due to fertilisers applied to farmland or to increased erosion when vegetation is lost. An excess of nutrients can lead to poor water quality, including algal blooms.

omnivory: Having a broad diet, including food from both animals and plants.

particulate nutrients: Nutrients (nitrogen and phosphorus) associated with solid material, such as sediments and detritus.

phytoplankton: Small algae that floats or is suspended in the water. Phytoplankton are responsible for the green appearance of water if there is an algal bloom, but phytoplankton are present at lower concentrations in healthy rivers, and are often an important part of the food web.

primary production: Growth of algae and plants. Primary production is ultimately the basis of the food-web, however increases in primary production in a river are sometimes associated with a deterioration in water quality, a shift towards growth of phytoplankton (algae floating in the water) in preference to other plants, and the possibility of algal blooms.

salinity: The amount of salt dissolved in water. Fresh water has a salinity of 0, whereas sea water has a salinity of 35. References to salinity are given as a unitless ratio on the practical salinity scale, but approximate to the same value in grams per litre, i.e. a salinity of 35 indicates approximately 35 g of dissolved substances (typically NaCl in seawater) per litre of water.

saturation oxygen concentration: The concentration at which oxygen dissolved in the water is in equilibrium with oxygen in the atmosphere. Above this concentration, oxygen will tend to move from water to the overlying air, while below this concentration, water will tend to absorb oxygen from the atmosphere. The saturation oxygen concentration is affected by several factors including temperature and salinity.

sediments: Particles such as soil, either suspended in the water or deposited on the bottom of the river. Sediments are washed into the river with flows from the catchment, and increases in sediment loads are associated with increases in flows and with changes to land use that increase erosion.

semi-diurnal: Twice-daily. There are two high tides, separated by low tides, in the Ord Estuary every day.

siltation: A river channel filling up with sediments.

spring tide: A higher than usual high tide, followed by a lower than usual low tide, which occurs about once per month. The opposite of a neap tide.

terrestrial: On dry land, or from the land. Terrestrial material in a river is material – such as soil and leaves from trees – that has been washed or blown into the river from the land.

tidal creek: A side-channel from an estuary which is influenced by tides and does not receive substantial fresh water inputs from a catchment of its own.

transfer efficiency: The efficiency with which biomass is passed up the food chain. If 10kg of algal production results in 1kg of additional fish biomass, the transfer efficiency is 10%.

trophic level: Position in the food-chain. Plants and animals at lower trophic levels are eaten by animals at higher trophic levels.

turbidity: A measure of the clarity of water (specifically, a measure of optical scattering). Highly turbid water in the Ord River estuary looks muddy and allows little light penetration, while the low-turbidity water in the freshwater zone (lower river) during the dry season looks more like tap-water.

zooplankton: Small animals such as insect larvae, that are transported with water.

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