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Integrated modelling for the conservation of river ecosystems: Progress in the South Australian River Murray

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Abstract: Investment in water infrastructure and management can enhance the ecological health of water-dependent ecosystems along highly regulated rivers. Investment in new flow-control infrastructure and management of both existing and new infrastructure can help return natural environmental flows to achieve healthy and representative areas of river ecosystems. In this paper, we developed an integrated model to cost-effectively restore environmental flows and ecosystem health in the River Murray in South Australia. The model integrates a range of hydrological, ecological, economic, and social components. A hydrological model is used to identify spatial and temporal inundation dynamics given flow rates and weir operation. Ecological response models were developed to link three aspects of environmental flows (flood duration, timing, and interflood period) to the health responses of ecosystem components. The infrastructure investments (flow-control regulators and irrigation pump relocation) were sited by interpreting high resolution LiDAR elevation data, digital orthophotography, and wetland mapping information; and their costs were quantified using a spreadsheet-based model. Social values were also estimated using a choice model quantifying willingness to pay for various ecosystem components and these were also included in the model. These diverse datasets and models were integrated in a decision support tool based on non-linear integer programming to investigate the cost-effectiveness of alternative flow levels and timing, existing flow-control infrastructure operation, and new infrastructure investment alternatives, given wider system constraints. The decision support tool can identify a suite of cost-effective infrastructure investments and a plan for their operation specifying where and when to capture and release water in riparian ecosystems. Outputs include a ranking of investment alternative and rules for managing flow-control infrastructure to achieve ecological and social values at minimum economic cost. In this paper we discuss the development and integration of the range of hydrological, ecological, economic, and social components of the model and the objectives of integrated river ecosystem management.

Keywords: planning, water, riverine, reserve, hydrology, environmental flows, regulation

1. INTRODUCTION

Many riparian, wetland, and floodplain ecosystems are highly stressed, primarily due to a lack of environmental flows at the quantity, timing, duration, frequency, rate of change, and quality required to sustain these ecosystems [Kingsford 2000, Bunn and Arthington 2002, Poff et al. 2007, Doll et al. 2009, Acreman and Ferguson 2010, Palmer et al. 2010, Poff and Zimmerman 2010]. Riparian ecosystems (e.g. water courses, wetlands, flood plains) along the River Murray in southern Australia have been threatened by the flow regulation and the overallocation of water resources for consumptive uses, increasing
salinity, turbidity, and nutrient levels, compounded by a series of drought years, and overlaid by long term climatic warming and drying trends [Walker and Thoms 1993, Goss 2003, McMahon and Finlayson 2003, Frazier and Page 2006, Gell et al. 2006, Bond et al. 2008, Nielsen and Brock 2009]. Despite the innate resilience of these ecosystems, some ecological processes and species may be threatened to the point of major irreversible change in ecosystem state. The restoration of natural environmental flows can reverse the ongoing degradation of riparian ecosystem processes and biodiversity [Arthington et al. 2010, Poff et al. 2010]. Under conditions of water scarcity, smart planning is required to deliver environmental flows which efficiently achieve both ecological and societal needs for freshwater [Baron and Poff 2002, O’Keefe 2009, Gordon et al. 2010].

Regulation of rivers has led to the homogenisation of these formerly-dynamic systems [Poff et al. 2007]. In the River Murray, regulation has attenuated large floods, eliminated low flows, and greatly increased moderate flows to meet irrigation and other human needs [Walker and Thoms 1993, CSIRO 2009]. In highly regulated river systems such as the River Murray, infrastructure such as regulators, dams, locks, and weirs used to store and release water for consumptive purposes can also be used to return river flows of appropriate quantity, timing, duration, frequency, and quality to enhance ecological health [Galat and Lipkin 2000, Bednarek and Hart 2005, Harman and Stewardson 2005, Lind et al. 2007, Richter and Thomas 2007, Holland et al. 2009, Poff et al. 2010]. Water releases from storages can be timed and combined with natural flows to return flooding cycles to now dry areas, and to return drying cycles to permanently-wet areas [Rood et al. 2005, Arthington et al. 2006].

Investments in new flow-control infrastructure can also be targeted for important areas and ecosystems whose environmental flows are more difficult or costly to restore using existing infrastructure. In concert with flow releases from storages, these structures can be operated such that they capture and hold water in wetlands at a specific frequency, at specific depths, and release it after a specific period of inundation. Alternatively, flow-control infrastructure can be used to dry out areas where current inundation regimes exceed that experienced under natural flows to reinstate their natural dry periods. Water savings made through reducing evaporation from permanently inundated wetlands can be used to achieve environmental flow benefits elsewhere..

Under the Australian Government’s $12.9B Water for the Future program, the South Australian (SA) Government’s Murray Futures Riverine Recovery project is charged with making investments in water infrastructure. Part of this program aims to achieve multiple ecological, hydrological, economic, and social objectives along the SA portion of the River Murray through infrastructure investment and management. This includes better management of existing flow-control structures (weirs), investment in and management of new flow-control structures (regulators), and moving irrigation off-take pumps where it restricts the ability to manipulate water levels in wetlands. The primary objective of the project is to enhance the ecological health of water course, wetland, and flood plain ecosystems. Further objectives include making water savings, improving water security for irrigators, and enhancing the social values for these systems. To inform cost-effective investment in, and management of, flow-control structures it is important to understand which areas, ecosystems, and species of the South Australian River Murray are of high conservation priority, and what infrastructure could be established and operated over time to best manage them.

In this paper, we describe the development of an integrated decision support tool for informing the investment in flow regulation infrastructure and flow management for cost-effectively achieving multiple environmental, economic, and social objectives in the SA River Murray. We provide a brief overview of the environmental flows allocation model, and describe the development of a diverse range of components that feed into the model including the hydrological inundation model, ecosystem mapping, ecological responses, economic costing of investments, and the social values mapping. The integration of these components within a decision support tool capable of finding near-optimal solutions to the allocation and management of environmental flows over space and time is essential for providing a solid evidence base for cost-effective investment of substantial amounts of
public money in riparian conservation. We finish by discussing future directions for integrated modelling of riparian ecosystem conservation.

2. INTEGRATED MODELLING OF ENVIRONMENTAL FLOWS

Planning for the return of environmental flows through infrastructure operation is a complex task. Riparian systems have spatially-heterogeneous ecological, economic, and social values, and are dominated by temporally-dynamic ecohydrological processes. Decisions on where to locate significant investments in flow-control infrastructure, and how to best operate this infrastructure over time to achieve multiple objectives are hard and involve multiple spatio-temporal trade-offs. Several reviews of the topic [e.g. Hughes and Rood 2003, Tharme 2003, Acreman and Dunbar 2004] have identified more than 200 techniques used to determine environmental flows. The simplest methods include lookup tables and desktop analysis, ranging through to more complex functional analysis and hydraulic habitat modelling. Arthington et al. [2006] states that in the past there has been a tendency to ignore the complexity of riparian systems in favour of simplistic and static rules for governing environmental flows. Arthington et al. [2010] called for a renewed focus on modelling complex eco-hydrological systems to find more acceptable and robust ways to manage rivers for multiple uses.

Solving this complex spatio-temporal problem has been the focus of water resource allocation planning for many years [Brumbelow and Georgakakos 2007, Harou et al. 2009]. In the past, studies have been focussed on the efficient delivery of water, particularly for use in irrigated agriculture and other human needs, often with the objective of maximising agricultural profitability [Cai 2008] or social welfare [Coram and Noakes 2009]. These studies have demonstrated that modelling and optimisation can increase the efficiency and reliability of water resources allocation for consumptive use [Abolpour and Javan 2007]. Increasingly, researchers are integrating ecological, economic, social values into water resource allocation [Brouwer and van Ek 2004, Loucks 2006, Brumbelow and Georgakakos 2007, Davis 2007, Brouwer and Hofkes 2008, de Lange et al. 2010]. Several studies have found that through integrating social and ecosystem perspectives, it is possible to identify restoration actions that both improve the health of riparian ecosystems and enhance the services provided to people by the ecosystem [Golet et al. 2006, Wang et al. 2009]. In addition, Golet et al. [2006] found that the process of including social values built trust with local stakeholders and enhanced local support for ecological restoration.

Previously, similar spatial, multi-period problems have been addressed through a variety of operations research techniques including stochastic dynamic programming [Tilmant et al. 2007], fuzzy logic [Abolpour and Javan 2007], metamodeling [Mousavi and Shourian 2010], goal programming [Xevi and Khan 2005], and elitist-mutated particle swarm optimization [Reddy and Kumar 2007]. Suen and Eheart [2006] used a genetic algorithm to quantify flow regimes that balanced ecological and human needs. Stewart-Koster et al. [2010] used Bayesian networks to guide investments in flow and catchment restoration for enhancing riparian ecosystem health. Tilmant et al. [2007] found that preferences of different water users required different environmental flows and operation rules for reservoir releases. To our knowledge, no studies have addressed the cost-effective investment of new flow-control structures and the operation of new and existing infrastructure over space and time for achieving multiple objectives.

3. STUDY AREA

The study area is the South Australian River Murray floodplain which encompasses the lower reaches of the river (Figure 1 Error! Reference source not found.). In the study area the river runs through semi-arid to Mediterranean agricultural land and is regulated by 6 weirs (referred to as Lock 1 – 6). The study area can be divided into valley, gorge, and swamps. The valley section from the SA border to Overland Corner is characterised by wide (5-10km) shedding flood plains with diverse wetlands including anabranches, billabongs (oxbows), and deflation basins. The gorge section from overland corner to Mannum is characterised by a narrower and less diverse flood plain (2 – 3km) constrained by 30m limestone cliffs within which the river meanders.
The swampland areas below Mannum are highly regulated and modified for agricultural production [Walker and Thoms 1993]. Major flood plain vegetation types include *Eucalyptus camaldulensis* (river red gum) and *E. largiflorens* (black box) communities. The study area provides important habitat for native water birds and fish species. The River Murray supplies water to high value irrigated horticulture and is one of the main sources of fresh water for the city of Adelaide and much of rural South Australia. The river is also the focus of significant social values particularly cultural and recreation values [Raymond et al. 2009]. Riparian ecosystems are currently highly stressed from the factors mentioned in the Introduction.

**Figure 1.** Location of the study area and flood plain, water courses, and wetlands along the South Australian River Murray.

### 4. MODEL COMPONENTS

#### 4.1 Hydrology

The hydrology component involves the development of river system hydrology modelling capacity to estimate flows over the South Australian border, the inundation of floodplains and flow between wetlands (connectivity) given river flows and weir manipulation, and return flows to the river following environmental watering.

In this paper, we focus on the inundation modelling using the River Murray Floodplain Inundation Model (RiM-FIM). RiM-FIM [Overton 2005] combines satellite imagery and digital elevation models to map the extent of flood plain inundation under a given flow rate and weir configuration. RiM-FIM uses Landsat TM imagery to identify areas inundated under a range of river flows. These flood extents were interpolated using the local topography as represented in a digital elevation model. Weirs can be raised by up to +50cm or lowered to -35cm, in 5cm increments. A hydrological model of backwater curves was used to capture the influence of weirs on inundation extent. We used RiM-FIM to map areas of inundation and wetland connectivity from each combination of river flow and weir height. This process also enabled us to quantify the flow level at which each wetland becomes inundated (or commence-to-fill) under each weir height.

**Figure 2.** Commence-to-fill flow rates for the Ral Ral/Woolenook/Murtho area with weir heights at 0 cm as calculated using RiM-FIM.

#### 4.2 River ecosystem mapping

We used a process of ecohydrological classification to map hydrologically-driven riparian ecosystems across the River Murray floodplain. This builds on the operational landscape unit approach proposed by Verhoeven et al. [2008] and vegetation-flow response guild approach of Merritt et al. [2010]. State government wetland and floodplain vegetation mapping was combined with RiM-FIM to define ecohydrological units. Wetland types included terminal, throughflow, overbank flow, saline swamp, and flood plain [Fee and
Scholz in prep, Jones and Miles 2009]. Flood plain areas were then classified into six ecohdrological types (emergent, lignum, riparian, floodplain, salt tolerant, and terrestrial dry). To do this we aggregated the 72 vegetation communities occurring on the flood plain based on the dominant vegetation type and overlaid this with the inundation regime derived from RiM-FIM, assigning commence-to-fill flow rates to each ecohdrological unit polygon using area-weighted averages. The outcome of this process was a map of 18 ecohdrological units in the study area (Figure 3).

<table>
<thead>
<tr>
<th>Ecohdrological units</th>
<th>Area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floodplain units</td>
<td></td>
</tr>
<tr>
<td>Riparian (River red gum)</td>
<td>18,664</td>
</tr>
<tr>
<td>Floodplain (Black box)</td>
<td>17,025</td>
</tr>
<tr>
<td>Emergent (Reeds)</td>
<td>2,569</td>
</tr>
<tr>
<td>Terrestrial dry (Chenopods)</td>
<td>8,597</td>
</tr>
<tr>
<td>Salt tolerant (Samphire)</td>
<td>9,425</td>
</tr>
<tr>
<td>Lignum</td>
<td>11,297</td>
</tr>
<tr>
<td>Water course units</td>
<td></td>
</tr>
<tr>
<td>Ephemeral Watercourse Reach</td>
<td>243</td>
</tr>
<tr>
<td>Seasonal Watercourse Reach</td>
<td>46</td>
</tr>
<tr>
<td>Permanent Watercourse Reach</td>
<td>1,409</td>
</tr>
<tr>
<td>Wetland units</td>
<td></td>
</tr>
<tr>
<td>Temporary Wetland - Overbank Flow</td>
<td>714</td>
</tr>
<tr>
<td>Temporary Wetland - Throughflow</td>
<td>1,836</td>
</tr>
<tr>
<td>Temporary Wetland - Terminal Branch</td>
<td>1,077</td>
</tr>
<tr>
<td>Permanent Lake - Throughflow</td>
<td>4,702</td>
</tr>
<tr>
<td>Permanent Lake - Terminal Branch</td>
<td>2,454</td>
</tr>
<tr>
<td>Terminal Lake</td>
<td>1,390</td>
</tr>
<tr>
<td>Permanent Swamp - Terminal Branch</td>
<td>338</td>
</tr>
<tr>
<td>Permanent Swamp - Throughflow</td>
<td>1,090</td>
</tr>
<tr>
<td>Saline Swamp</td>
<td>1,385</td>
</tr>
</tbody>
</table>

Figure 3. Area of ecohdrological units mapped across the study area and an example of ecohdrological units occurring in the Ral Ral/Woolenook/Murtho area.

4.3 Quantifying Environmental Flows

Modelled hydrographs detailing flows over the South Australian border under natural flows (no regulation) and current (with existing regulation) from 1895 to 2006 (Figure 4) were taken from CSIRO [2008]. Using these hydrographs we calculated indicators of inundation for environmental flows after Richter et al. [1996] including flood duration, timing, and inter-flood period for each flow level from a base flow of 5,000 ML/day to 109,000 ML/day in intervals of 1,000 ML/day using R.

Figure 4. Modelled natural (navy line) and current (burgundy area) daily hydrographs from 1921 – 2006 for the River Murray at the South Australian border [CSIRO 2008].

We then allocated inundation indicator values to each ecohdrological unit polygon in the study area using commence-to-fill flow rates from RiM-FIM. This enabled us to identify the spatial extent of flooding and the ecohdrological units inundated under different combinations of flow rates and weir heights as a direct input to the decision analysis model. We summarised inundation indicators (flood duration, timing, and inter-flood period) under the natural hydrograph to quantify the natural flow regime [Poff et al. 1997] of each ecohdrological unit. This natural flow regime provided an objective for the restoration of environmental flows of ecohdrological units in the integrated decision analysis model.

4.4 Ecological responses to environmental flows

We developed ecological response functions for floodplain and riparian vegetation types, wetland vegetation, water birds, and fish to quantify the effect of environmental flows on the health of river ecosystems [Shafroth et al. 2010]. Floodplain and riparian vegetation
types included black box woodland, floodplain red gum woodland, riparian red gum woodland, lignum (*Muehlenbeckia florulenta*) shrubland, salt-tolerant vegetation, and chenopods. Wetland vegetation types included rats tail couch grassland, ribbon weed herbland, and *Phragmites australis*. Water birds included colonial nesting water birds, and water fowl and grebes. Fish communities included flood spawners, wetland specialists, freshwater catfish, main channel generalists, main channel specialists, low flow specialists.

Ecological responses quantified the health of these ecological features on a scale from 0 - 1 as a function of environmental flow characteristics. Ecological response functions were developed for flood timing (using calendar months), duration (usually in days), and inter-dry period (i.e. the length of time between inundation events, in months). Where relevant, separate response curves were included for different life stages (e.g. seedlings and adults for vegetation and spawning, juveniles and adults for fish).

![Figure 5. Example of an ecological response function for the health of colonial nesting water birds against inter-flood duration from Young et al. [2003].](image)

Ecological response functions were based on the Murray Flow Assessment Tool (MFAT; Young et al. 2003). Young et al. (2003) synthesised ecological response functions for several ecological components for nine zones along the River Murray and its tributaries. Ecological response functions for flood plain vegetation were refined using an analysis of environmental flows under the natural hydrograph. We calculated the mean inundation duration and inter-flood period for ecohydrological areas and assumed that environmental flows within 1 standard deviation of the mean were most conducive to the healthy growth and function of these units. We used this data-derived information to update the ecological response curves from Young et al. [2003]. Additional information from Overton et al. (2009) and Ecological Associates (2010) was also used to modify the response functions where available. A final modification was to only use responses of zero when it was likely that populations would become locally extinct.

Ecological response functions were then linked to mapped ecohydrological units in order to relate biota to the habitat in which it was most likely to be found. Faunal species were linked to ecohydrological units based on habitat preference information [Young et al. 2003, Overton et al. 2009, Ecological Associates 2010] and expert opinion. Each ecological feature for which we assembled a response function was assigned a probability of occurrence in each ecohydrological unit type. Probability scores ranged between 0, if a community was not likely to utilise the ecohydrological unit habitat (e.g. fish that are main channel specialists are not likely to use the floodplain even when it is inundated), to 1 if the ecohydrological unit was likely to be core habitat (e.g. watercourse reaches for fish that are main channel specialists). Scores of 0.5 were allocated for marginal habitat, or if there was a moderate possibility that the habitat would be used, and 0.25 if it was unlikely, but possible, that the habitat would be used. Life history stages were differentially assigned where seedlings, larvae or juveniles utilised different habitat types to adults.

### 4.5 Economic costs

We grouped wetland ecohydrological unit polygons into 80 complexes as basic investment decision units. We quantified the establishment costs of capital investment in each wetland complex inclusive of regulator construction and moving irrigation pump off-takes to the main channel. First, we identified wetlands which could feasibly be regulated. Each wetland/water course polygon was interpreted using LiDAR elevation data, commence-to-fill data from RiM-FIM, and high resolution aerial orthophotography. Regulators were intelligently positioned in the neck of inlets at appropriate widths and depths to keep wetlands full at rim height. Regulator widths and depths were input into a model (Tonkin Consulting, unpublished model) to calculate infrastructure costing. To cost the relocation
of irrigation off-take pumps we identified pump locations from pump and meter data. To cost the relocation of off-takes to the main river channel, we intelligently digitised pipelines which took the shortest route, efficiently connecting all pumps, where possible followed roads and avoided steep grades and dense vegetation. We input pipe length, flow and head data as inputs into a model (Tonkin Consulting, unpublished model) to calculate the cost of relocating pumps from wetlands to the main channel. The total cost of all investments including the 153 potential new regulators, 64 km of new pipe and 36 new pumps, was over S117 million. Ongoing operation and maintenance costs were not considered.

![Figure 6](image.png)

**Figure 6.** Example of the siting of regulators for controlling flows and piping for relocating irrigation off-takes in the Lake Bywaters/Walker Flat area. Elevation data is from LiDAR.

### 4.6 Social values

To capture the priorities for society and the values assigned to different attributes of the floodplain vegetation, wetlands and river channel, we used the willingness to pay estimates for South Australia from a major national survey undertaken in 2009 (Hatton MacDonald et al., under review). People use the River Murray for water based recreation, camping and fishing and receive a series of direct use values. They also receive non-use or existence benefits from improving the quality of a natural resource apart from any actual use. To provide estimates of these values, 1000 South Australian households (63.6% responded) were asked to consider a set of choice experiments where they were offered the status quo health of the Murray River and Coorong as well as two options which involved different levels of health of particular assets and different costs. By presenting different combinations of the attributes and different household costs, respondents face different trade-offs. The probabilities of different choices and willingness to pay for improvements were estimated and used to weight the ecological responses associated with frequency of bird-breeding, native fish populations, floodplain vegetation and the major wetlands including the Coorong and Lower Lakes.

### 5. INTEGRATED MODELLING

The diverse sources of hydrological, ecological, social, and economic information described above need to be integrated to identify cost-effective ways of locating and managing water resources over time. We built an optimisation model based on non-linear integer programming to analyse this complex spatio-temporal problem. The model seeks to select the suite of wetland complexes to invest in regulator construction and pump relocation. In addition, the model identifies the optimal management of these new regulators and existing regulators and weirs over time to return natural environmental flow regimes.

We used the current hydrograph of River Murray flows at the South Australian border for the 20 years from 1986 – 2006 in our model. The basis of the model is the hydrological dynamics quantified by the RiM-FIM model which identifies the ecohydrological units inundated. The amount of water in each ecohydrological unit in each month depends on the flow at the border, the commence-to-fill flow rate of ecohydrological units, weir heights, water losses, whether regulators are built to control flows and whether they are open or closed.

The decision variables include a yes/no decision on whether each of the 80 complexes is selected for investment. Other decision variables operate the weir and regulator infrastructure at monthly time steps. At each of the 240 monthly time steps, each regulator
may be either open or closed and the height of each of the 6 weirs in the study area may be adjusted. Thus, given the amount of flow at the border, infrastructure may be operated to return wetting and drying cycles to ecolhydrological units and their ecological components that are more typical of their natural flow regime in terms of duration, timing, and frequency of inundation. The major constraints applied in the model were that the cost of new regulators and irrigation pump relocation must be within the total available budget, and several specific rules which governed weir operation.

The objective of the model is to achieve environmental flows for each ecological component, as close as possible to the natural flow regimes. Areas of each ecological component occurring at each level of inundation duration, timing, and inter-flood period were summarised. The model aims to maximise the proportion of the area that experiences environmental flows closer to its natural flow regime, weighted by the ecological response functions (Figure 7). This is done across all ecological components as multiple ecological responses were multiplied to give an overall response for each habitat unit. Ecological response was then weighted by social values at a ratio of 5(ecological):1(social).

We used compromise programming principles (least squares differences) to ensure that the representation of ecological components progresses towards that of the natural hydrograph without undesirable over or under representation of some components. This undesirable outcome may be unavoidable if it is not possible to water key wetlands/floodplains under a current hydrograph. The objective function also has flexibility to put higher priorities on some species to represent conservation priorities.

The formulated non-linear integer programming problem contains about 25,000 decision variables for the study area. With such a large and computationally complex investment decision problem, finding a guaranteed optimal solution is impossible. Instead, we used a tabu search meta-heuristic to find good solutions. The outputs are a list of investments that appear most often in good solutions found by the model. Outputs also include comprehensive weir and regulator operation rules for returning natural flows to a representative area of river ecosystems in the study area.

6. CONCLUSION

Achieving better ecological health outcomes for highly regulated rivers such as the South Australian River Murray requires consideration of how natural environmental flows can be returned through the management of existing and new flow-control infrastructure. Additionally, it is important to consider how infrastructure investment and flow management strategies are likely to impact upon social values for these systems. We provided an example of the assembly of a variety of hydrological, ecological, social and economic information and how it can be integrated to inform cost-effective investment and management decisions for river ecosystems over time. River ecosystems and water resources management involve complex spatial and temporal processes. The integration of hydrological, ecological, social and economic information in a decision analysis model was
essential for identifying cost-effective solutions for managing the health of river ecosystems so they can continue producing the many services that society relies on. Future work needs to consider the potential ecological and social benefits achieved by increasing flows over the South Australian border. By purchasing additional water on the market and by the strategic timing and delivery of that water through the operation of upstream storages, we can effectively modify environmental flows (current hydrograph). This can be done strategically to complement the operation of existing and new infrastructure in restoring natural flows to ecohydrological units.

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