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Integrated modelling of cost-effective siting and operation of flow-control infrastructure for river ecosystem conservation

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[1] Wetland and floodplain ecosystems along many regulated rivers are highly stressed, primarily due to a lack of environmental flows of appropriate magnitude, frequency, duration, and timing to support ecological functions. In the absence of increased environmental flows, the ecological health of river ecosystems can be enhanced by the operation of existing and new flow-control infrastructure (weirs and regulators) to return more natural environmental flow regimes to specific areas. However, determining the optimal investment and operation strategies over time is a complex task due to several factors including the multiple environmental values attached to wetlands, spatial and temporal heterogeneity and dependencies, nonlinearity, and time-dependent decisions. This makes for a very large number of decision variables over a long planning horizon. The focus of this paper is the development of a nonlinear integer programming model that accommodates these complexities. The mathematical objective aims to return the natural flow regime of key components of river ecosystems in terms of flood timing, flood duration, and interflood period. We applied a 2-stage recursive heuristic using tabu search to solve the model and tested it on the entire South Australian River Murray floodplain. We conclude that modern meta-heuristics can be used to solve the very complex nonlinear problems with spatial and temporal dependencies typical of environmental flow allocation in regulated river ecosystems. The model has been used to inform the investment in, and operation of, flow-control infrastructure in the South Australian River Murray.

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1. Introduction

[2] 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; *Acreman and Ferguson*, 2010; *Palmer et al.*, 2010; *Poff and Zimmerman*, 2010]. Also, some wetlands are degraded due to permanent inundation. In highly regulated river systems, infrastructure such as dams, weirs, and regulators used to store and release water for consumptive purposes can also be used to return natural environmental flows [*Poff et al.*, 2007] to enhance ecological health [*Galat and Lipkin*, 2000; *Bednarek and Hart*, 2005; *Harman and Stewardson*, 2005; *Lind et al.*, 2007; *Holland et al.*, 2009]. A regulator is a gate that opens and closes to hold water in or out of a wetland and is the most common flow-control infrastructure used in river and wetland locations. A weir is a large in-channel regulatory structure that can be altered to change river stage height and flow. 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].

[3] Planning for the return of environmental flows through infrastructure operation is a complex task. Riparian systems have spatially-heterogeneous ecological values and are dominated by spatial dependencies and temporally-dynamic hydrological and ecological 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 decisions and trade-offs. *Arthington et al.* [2006] state that the increasing tendency of water managers to favor simplistic and static rules for governing environmental flows is misguided and is likely to lead to the further degradation of river ecosystems. *Arthington et al.* [2010] called for a renewed focus on modeling the full complexity of ecohydrological systems to find more acceptable and robust ways to manage environmental flows for river ecosystems.

[4] The literature is rich with methodologies to optimally alter river flow to improve environmental or agricultural

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objectives. Previously, similar spatial, multiperiod 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], meta-modeling [*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.

[5] Many conservation-oriented studies have aimed to restore components of the river's natural environmental flow regime [*Poff et al.*, 2007; *Arthington et al.*, 2006], despite being unable to return large volumes of water to the environment. To restore natural flows in river ecosystems, most attention has been focused on reservoir releases [e.g., *Schluter et al.*, 2005; *Richter and Thomas*, 2007; *Tu et al.*, 2003; *Cardwell et al.*, 1996] and we describe two of the most relevant works here. The first study, by *Suen and Eheart* [2006], implemented a multiobjective model to produce management targets for a reservoir to satisfy a balance of downstream aquatic ecosystem health and human needs. The model used ecohydrological indicators contained in the Taiwan Ecohydrology Indicator System to represent the ecosystem response. The hydrograph was generated using historical flow data with fuzzy set theory applied to represent disturbance levels. The multiobjective linear programming model was solved using a multiobjective genetic algorithm. The second study, by *Schluter et al.* [2006], developed a GIS-based decision support tool, TUGIA, and used it to assess the ecological effects of altering water management strategies in the Amudarya River, central Asia. It is a modularised tool that combines multiobjective water allocation (monthly discharge) with spatially-explicit statistical and rule-based models of landscape dynamics.

[6] Improving ecological health by optimizing the use of other river infrastructure beyond reservoir releases (e.g., weirs, regulators) has had limited attention in the scientific literature. In the case of a single weir, *Debecker et al.* [2006] applied artificial neural networks to optimize the prediction of habitat suitability in the possible event of removing a weir. *Shiau and Wu* [2007] applied multiobjective optimization to flow regimes and the operation of a diversion weir to achieve an optimal trade-off between ecological and human needs. Their model incorporated seasonal and inter-annual flow variability through different solutions generated along a Pareto front using multiobjective optimization. More recently, *Shiau and Wu* [2009] accommodated inter-annual flow variability through using a single long-term flow regime (1959–2003).

[7] A primary contribution of our paper is addressing a river system where there are multiple infrastructures (weirs and regulators) to be optimized simultaneously to achieve ecological benefits. The model addresses the real-world planning question of the selection of a cost-effective suite of investments in establishing new flow-control infrastructure given a limited budget. It also identifies the optimal operation of this infrastructure to control flows in water course, floodplain, and wetland ecosystems with the aim of returning natural environmental flows in terms of flood timing, duration, and interflood period, using the River Murray in South Australia (SA) as a case-study. It is a complex, nonlinear problem, since investment and operating decisions at one site affect investment and management decisions and their ecological consequences at other sites. In this paper, we formulate this problem as a multiperiod, nonlinear integer programming model consisting of interlinked hydrological and ecological components. We propose a tabu search meta-heuristic strategy for solving the optimization problem. We apply the model to the River Murray in South Australia, and provide illustrative outputs of the nature of the investments in new infrastructure. Operation of new and existing infrastructure for achieving ecological values in river ecosystems is also captured in the model. The model was used to inform investment in and operation of flow-control infrastructure under the AUD 110 million Murray Futures Riverine Recovery program in South Australia as part of the Commonwealth Water for the Future program.

2. Mathematical Representation

[8] In this section, we formulate a mathematical programming model to optimize the operations of flow control infrastructure (regulators and weirs) in a river system over a planning time horizon (e.g., 20 years), to maximize ecological outcomes. It accommodates operational rules of infrastructure along with temporal features of water flow in the river system and multiple ecological indicators. The resulting model has a large number of parameter and variable definitions, which we introduce in section 2.1. Figure 1 illustrates the framework for the entire model and solution method, and shows the primary inputs/outputs, variables, constraints, objective and solution method, which are defined in detail throughout section 2 and 3.

2.1. Input Parameters

[9] I is the set of indices $i \in I = \{1, \ldots, n', \ldots, n\}$ for the existing regulated wetland complexes n' and potential new ones $n - n'$. The fundamental spatial decision-making for investment and operation of regulators is the wetland complex. Wetland complexes usually require investment in multiple regulators to control flows. All regulators within a complex must be operated simultaneously. These regulators control the opening and closing that provide water to ecohydrological polygons linked to that regulated complex. Flow can only be controlled by regulators in wetlands (i.e., as opposed to floodplain units), although not all wetlands are regulated.

[10] C_i is the cost of building a new regulators and other infrastructure for wetland complex $i \in I$. Investment in wetland complexes includes the construction cost for new regulators as well as the upfront costs of relocating irrigation off-take pumps from the wetland to the main river channel so that the reintroduction of wetting and drying regimes to wetlands does not impinge on the water security of irrigators.

[11] B is the budget for investment in new regulators and other infrastructure.

[12] J is the set of indices $j \in J$ represent the set of individual and spatially distinct areas (polygons) of a specific ecohydrological type.

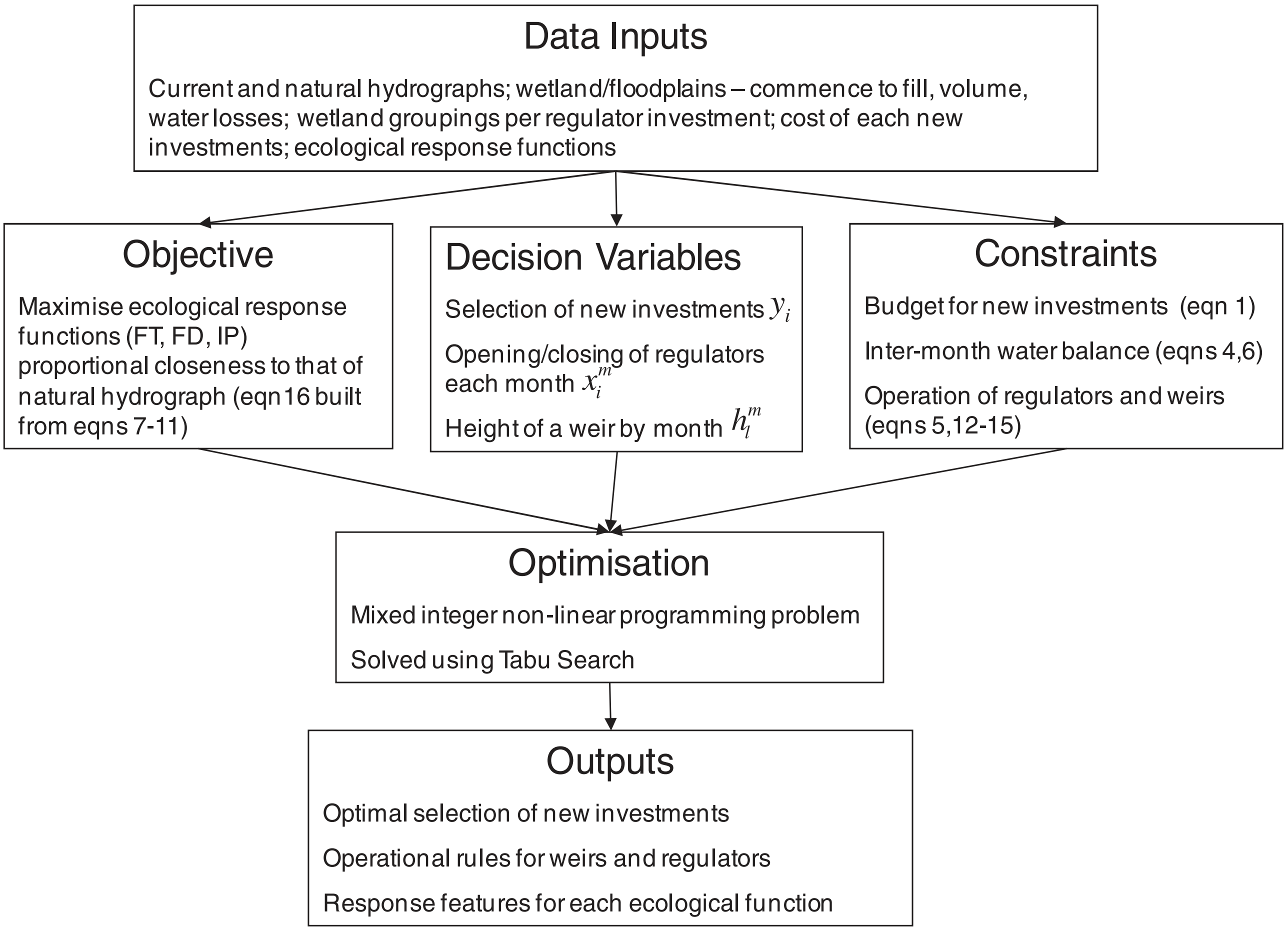

Figure 1. Model framework showing inputs, outputs and components. Ecological response functions are Flood Timing (FT), Flood Duration (FD), and Interflood Period (IP).

[13] a_j is the area of ecohydrological polygon $j \in J$, measured in hectares

$$f_i^j = \begin{cases} 1 & \text{if eco-hydrological polygon } j \in J \text{ is linked to} \\ & \text{regulated complex } i \in I \\ 0 & \text{otherwise} \end{cases}$$

[14] K is the set of indices $k \in K$ of ecological components which occur in specific ecohydrological polygons where $k \in$ {black box woodland, river red gum woodland, colonial nesting waterbirds, etc}.

[15] q_j^k is the probability of eco-hydrological polygon $j \in$ containing ecological component $k \in K$.

[16] L is the set of indices $l \in L$ representing weirs. Along the South Australian River Murray $L = 6$ (number of weirs), which also represent the set of river sections of interest across the Murray catchment. A river section represents the part of the river between weirs $l \in L$ and $l - 1 \in L$. The ecohydrological polygon is linked at a weir if it is upstream to the weir and the inundation of the polygon is influenced by the raising or lowering of the weir.

$$b_j^l = \begin{cases} 1 & \text{if eco-hydrological polygon } j \in J \text{ is linked to} \\ & \text{to weir } l \in L \\ 0 & \text{otherwise} \end{cases}$$

[17] c_j^{wh} commence-to-fill flowrate (ML/day) required to start filling ecohydrological polygon $j \in J$, when the weir height is at height wh. This is the flowrate either from the water source (e.g., dam) or at the most upstream point of the river system under consideration. The weir height wh is measured in centimetres, and based on existing weir operation rules, weir heights can be set at levels $wh \in WH$. The commence-to-fill values are lower for higher weir heights since a raised weir require a lower main channel flowrate to achieve flooding into the ecohydrological polygon. Ecohydrological polygon $j \in J$ can only be affected by the immediate downstream weir as per b_j^l.

[18] M set of indices $m \in M = \{1, \ldots, HO\}$ representing the monthly steps in the planning horizon, where $HO =$ number of months. The planning horizon needs to be long enough to accommodate seasonal variability and the long time horizon of the ecological response functions for some ecological components. For example the desirable interflood period for some terrestrial vegetation can be >3 years.

[19] In this study we use current and natural hydrographs (daily flow rates at the South Australian border as modeled by Murray-Darling Basin Sustainable Yields project) [*Commonwealth Scientific and Industrial Research Organisation* (*CSIRO*), 2008]. The current hydrograph represents flows given current climate, river operations, and licensed

water extractions. The natural hydrograph represents flows under current climate if there were no regulation or extractions. Several parameters are used to define the water supply for current and natural hydrographs:

[20] r^m is the average water supply (ML/day) in month $m \in M$ that can be made available for all ecohydrological polygons, under a current hydrograph. This is the water supply from the dams or at the most upstream point of the river system under consideration.

[21] p^m is the peak daily water supply (ML/day) in month $m \in M$ that can be made available for all ecohydrological polygons, under a current hydrograph. For the case study in this paper both r^m and p^m are fixed inputs since the hydrograph is not modified by water releases from the upstream reservoirs.

[22] w_j is the volume of water (ML) required to fill ecohydrological polygon $j \in J$ from empty.

[23] o_j^m is the expected water lost (ML) from ecohydrological polygon $j \in J$ from leakage and evaporation.

2.2. Decision Variables

[24] We specified three sets of decision variables in this study. The first set of decision variables is binary and defines the eligible wetland complexes for investment in regulators:

$$y_i = \begin{cases} 1 & \text{if regulators are constructed for wetland complex } i \in I \\ 0 & \text{otherwise} \end{cases}$$

$$y_i = 1 \text{ for } \forall i \leq n'$$

[25] The second set of decision variables is also binary and defines how existing and new regulators are operated in wetland complexes:

$$x_i^m = \begin{cases} 1 & \text{if regulators in complex } i \in I \text{ are open in month } m \in M \\ 0 & \text{otherwise} \end{cases}$$

[26] The third set of decision variables governs the height for each weir. We use integer increments (e.g., cm) rather than continuous increments such that:

$$h_l^m = \text{Height Of Weir } l \in L \text{ In Month } m \in M$$

[27] The decision variables y_i, x_i^m, h_l^m are optimized simultaneously within the solution methodology. Let *X*, *H*, *Y* represent vectors of the decision variables x_i^m, h_l^m, y_i, respectively. To reduce the number of decision variable categories, selection of new regulators for wetland complex y_i are controlled by its operation x_i^m. That is, y_i is set to 1 automatically if the regulators in the complex are operated.

2.3. Other Variables

[28] The following variables are dependent on the decision variables defined above:

[29] s_j^m is the stock of water (ML) in each ecohydrological polygon $j \in J$ at the end of month $m \in M$.

$$d_j^m = \begin{cases} 1 & \text{if flow into eco-hydrological polygon } j \in J \\ & \text{in month } m \in M \text{ is achievable} \\ 0 & \text{otherwise} \end{cases}$$

[30] $d_j^m = 1$ where the flowrate along the river is greater than the commence-to-fill flow value of ecohydrological polygon $j \in J$, subject to the regulators in complex $i \in I$ being open. If $d_j^m = 0$ water will drain from the ecohydrological polygon, unless the regulators in the complex are closed. The reuse of water drained back into the river channel is not considered in the current version of the model.

$$g_j^m = \begin{cases} 1 & \text{eco-hydrological polygon } j \in J \text{ in month } m \in M \\ & \text{is inundated with water} \\ 0 & \text{otherwise} \end{cases}$$

[31] For this paper we assume $g_j^m = 1$ if ecohydrological polygon $j \in J$ is more than 80% full ($s_j^m \geq 0.8w_j$), though this percentage can be changed. If $g_j^m = 1$, ecohydrological polygon $j \in J$ is considered to have a minimal desirable volume of water. While 80% was used for the case study of this paper, in the absence of detailed data on suitable water depth, this value can be modified for other applications.

2.4. Constraints

2.4.1. Budget

[32] A constraint was set on the total available budget for new flow control infrastructure investment:

$$\sum_{\substack{i \in I \\ i > n'}} C_i \cdot y_i \leq B \tag{1}$$

2.4.2. Water Flow

[33] The following constraints are used to automatically set the variable $d_j^m = 1$ if the peak daily water supply is greater than the commence-to-fill flow value for the polygon $j \in J$:

$$p^m \geq c_j^{h_l^m} - (1 - d_j^m) \cdot N \; \forall j \in J, m \in M, b_j^l = 1 \tag{2}$$

$$p^m < c_j^{h_l^m} - d_j^m \cdot N \; \forall j \in J, m \in M, b_j^l = 1 \tag{3}$$

where N is a big number (e.g., $10e^9$). If the commence-to-fill flow value was less than the peak daily water supply, d_j^m would have to equal 1 for both constraints to be satisfied.

[34] The next constraint ensures the total amount of water entering the ecohydrological polygon in month $m \in M$ must be less than or equal to the available water in month $m \in M$, accommodating water set aside for other uses.

$$\begin{aligned} &\sum_{i \in I} \sum_{j \in J} f_i^j \cdot x_i^m \cdot (1 - x_i^{m-1}) \cdot (w_j - s_j^{m-1}) \cdot d_j^m \\ &\quad + \sum_{j \in J} d_j^m \cdot (w_j - s_j^{m-1}) \leq r^m \cdot t^m \; \forall m \in M \end{aligned} \tag{4}$$

where t^m is the number of days in month $m \in M$. The first double summation refers to the filling of wetlands through the opening of the regulator(s), when the regulator(s) was closed in the previous month. The second summation component refers to the filling of ecohydrological polygons (unregulated wetlands and flood plains) influenced by the raising of the associated weir. The term $w_j - s_j^{m-1}$ in both summations refers to the water that is added (or topped up to full) in the ecohydrological polygon, allowing for the fact it may not be empty to begin with.

[35] Only existing regulators or regulators in selected new wetland complexes can be operated:

$$x_i^m \leq y_i \; \forall m \in M, i \in I \tag{5}$$

[36] Next is the balance equation for water volume flow in each ecohydrological polygon. It calculates the amount of water in polygon $j \in J$ in month $m \in M$ as equal to the amount of water in month $m - 1 \in M$ minus the water losses in month $m \in M$ plus the amount of water that enters through inundation minus the amount of water that is released:

$$\begin{aligned} s_j^m = {} & s_j^{m-1} - o_j^m + \sum_{i \in I} x_i^m \cdot (1 - x_i^{m-1}) \cdot f_i^j \cdot (w_j - s_j^{m-1}) \cdot d_j^m \\ & + (w_j - s_j^{m-1}) \cdot d_j^m - (s_j^{m-1} - o_j^m) \cdot \sum_{i \in I} x_i^m \cdot (1 - x_i^{m-1}) \\ & \cdot f_i^j \cdot (1 - d_j^m) - (s_j^{m-1} - o_j^m) \cdot d_j^m \; \forall j \in J, m \in M \end{aligned} \tag{6}$$

[37] Water enters or is released from the ecohydrological polygon as a function of the commence-to-fill flow value and river flow rates, as well as weir and regulator operations. As with equation (4), the components in equation (6) refer to the filling of the ecohydrological polygon via the regulator or weir (not simultaneously). The term $w_j - s_j^{m-1}$ in the first and second summations refers to the amount of water being added to fill it. The second half of equation (6) refers to emptying of the polygons when either the regulator is opened when river flows are less than the polygon's commence-to-fill flow values, or the weir is lowered. The term $(s_j^{m-1} - o_j^m)$ refers to the amount of water removed to empty it. If emptied, we assume it is emptied completely (i.e., $s_j^m = 0$). For the current version of the model, water that is emptied from ecohydrological polygon $j \in J$ is not returned to the available water allocation in equation (4). This will be a future extension of the model.

2.4.3. Ecological Response Functions

[38] A goal in this model was to achieve optimal ecological responses under a current hydrograph, which are as close as possible to responses that would be achieved under a natural hydrograph. We developed functions to characterize the responses of key ecological components to changes in environmental flows [see also *Young et al.*, 2003]. Our response functions were based on three commonly-used hydrological indicators: flood timing (FT); flood duration (FD); and interflood period (IP) [*Young et al.*, 2003; *Schluter et al.*, 2006]. Other hydrological indicators such as the rate of rise and fall, Daily Flow Percentile and Spawning Flow Magnitude are also important for some ecological components. However, they were not included in the current model to constrain the modeling requirements and in many cases have minimal impact from the operation of weirs and regulators. Ecological response functions were used to specify how the health of each ecological component varies with each of the hydrological indicators. Health was measured as a score between 0 (poor) and 1 (good). Ecological components were mapped to ecohydrological polygons such that each component may occur in one or more polygon(s).

[39] For FT, we calculate the total area (hectares) across the ecohydrological polygons that achieve a minimal volume of water (or desirable inundation) in each calendar month. Let $FT_{k,l}^{mc}$ equal the total area of ecohydrological polygons of ecological component $k \in K$, with a sufficient volume of water in calendar month $mc = \{1,2,3,4,5,6,7,8,9,10,11,12\}$ for river section $l \in L$:

$$FT_{k,l}^{mc} = \sum_{j \in J} \sum_{m \in M} b_j^l \cdot q_j^k \cdot a_j \cdot g_j^m, \tag{7}$$

where

$$s_j^m \geq 0.8 \cdot w_j - (1 - g_j^m) \cdot N \; \forall j \in J, m \in M \tag{8}$$

$$s_j^m < 0.8 \cdot w_j - g_j^m \cdot N \; \forall j \in J, m \in M \tag{9}$$

[40] mc is the calendar month of m. We also define MFT_k^{mc} as the ecological health response (between 0 and 1) for ecological component $k \in K$ when flooding occurs in calendar month mc. The likelihood of each ecological component was given a rating between 0 and 1 for each mc where 1 indicated a suitable habitat for that ecological component, and we expect that it would be used by the component. If $MFT_k^{mc} = 0$ it would not be suitable habitat for the ecological component and it was unlikely to be used. Constraints (8) and (9) have a similar function to constraints (2) and (3) in that they force variable g_j^m to =1 if the water level in $j \in J$ is greater than 80% of its capacity.

[41] For FD, we calculate the total area of ecohydrological polygons maintaining a flood duration of mi months. Let $FD_{k,l}^{mi}$ = total hectares maintaining flood duration of mi months, by river section $l \in L$ by ecological component $k \in K$.

$$FD_{k,l}^{mi} = \sum_{j \in J} \sum_{m \in M} b_j^l \cdot q_j^k \cdot a_j \cdot \prod_{mm=1}^{mi} g_j^{m+mm} \tag{10}$$

[42] We define MFD_k^{mi} as the health response (between 0 and 1) for ecological component $k \in K$ when inundation occurs for mi months.

[43] For IP, we calculate the total area of ecohydrological polygons maintaining an inter-flood period of mi months. Let $IP_{k,l}^{mi}$ = total hectares of maintaining an inter-flood period for mi months, by river section $l \in L$ by ecological component $k \in K$.

$$IP_{k,l}^{mi} = \sum_{j \in J} \sum_{m \in M} b_j^l \cdot q_j^k \cdot a_j \cdot \prod_{mm=1}^{mi} (1 - g_j^{m+mm}) \tag{11}$$

[44] We define MIP_k^{mi} as the health response (between 0 and 1) for ecological component $k \in K$ when an inter-flood period occurs for mi months.

[45] $FT_{k,l}^{mc}$, $FD_{k,l}^{mi}$ and $IP_{k,l}^{mi}$ are calculated based on the current hydrograph r^m, p^m. Let $NFT_{k,l}^{mc}$, $NFD_{k,l}^{mi}$ and $NIP_{k,l}^{mi}$ be corresponding indicators calculated for the natural

hydrograph. The indicators for the natural hydrograph are not dependent upon the decision variables and are calculated prior to initiating the optimization algorithm. *Overton et al.* [2010] provides further details of how these ecological response functions were constructed for the case study using data available for the South Australian River Murray.

2.4.4. Operations of the Weirs

[46] Operational rules on weirs were also required to manage water stress levels between upstream and downstream weirs, and meet safety requirements of moving the weir structures within a given month.

[47] Constraints for $\leq \alpha$ cm change in weir height between months are

$$h_l^m - h_l^{m-1} \leq \alpha \tag{12}$$

$$h_l^m - h_l^{m-1} \geq -\alpha\,. \tag{13}$$

[48] Constraints for $\leq \beta$ cm difference between neighboring weirs are

$$h_l^m - h_{l-1}^m \leq \beta \tag{14}$$

$$h_l^m - h_{l-1}^m \geq -\beta\,. \tag{15}$$

2.5. Objective Function

[49] The objective function aims to keep the ecological response functions $FT_{k,l}^{mc}$, $FD_{k,l}^{mi}$ and $IP_{k,l}^{mi}$ proportionally as close as possible to the corresponding functions $NFT_{k,l}^{mc}$, $NFD_{k,l}^{mi}$ and $NIP_{k,l}^{mi}$ based on a natural hydrograph. To achieve this, we implemented a minimized least-squares approach, as follows:

$$\begin{aligned}\text{Min Z}= &\sum_{mc}\sum_{k\in K}\sum_{l\in L} MFT_k^{mc}\cdot(FT_{k,l}^{mc}-NFT_{k,l}^{mc})^2\\ &\cdot\sum_{mi}\sum_{k\in K}\sum_{l\in L} MFD_k^{mi}\cdot(FD_{k,l}^{mi}-NFD_{k,l}^{mi})^2\\ &\cdot\sum_{mi}\sum_{k\in K}\sum_{l\in L} MIP_k^{mi}\cdot(IP_{k,l}^{mi}-NIP_{k,l}^{mi})^2\end{aligned} \tag{16}$$

where the least-squares difference for FT, FD and IP are multiplied together due to the general lack of information regarding the relative importance of each response indicator. The development of an objective function for this type of model has received very little attention in the past. We chose to use a multiplicative function because we wanted to capture the feature of a very low score for one ecological response function leading to a low objective function value regardless of the other response functions. This is an area of ongoing research.

3. Solution Method

[50] The model represented by equations (1) to (16) is a nonlinear integer programming problem. By considering variables y_i, it is an extension of the capacitated P-median problem [*Bramel and Simchi-Levi*, 1997], with additional decision variables x_i^m, h_l^m. This is very difficult to solve for real-world problems of reasonable size using commercial software packages. Lagrangean Relaxation is a popular method to solve the capacitated P-median or location problem [e.g., *Ghiani et al.*, 2002; *Christofides and Beasley*, 1983]. Unlike the capacitated P-Median problem, the large number of nonlinear and complexity constraints (1)–(15) make it difficult to apply Lagrangean Relaxation, since the subproblems are still difficult to solve to optimality.

[51] By solving only for x_i^m and h_l^m the model is similar to an assignment problem, in terms of assigning the operations of the regulators/weirs to each month in the planning horizon with some regulators/weirs being assigned to multiple months. However, the assignment problem is subject to dynamic constraints represented by constraints (4) and (6). Such a problem has been shown to be NP-Hard [*Fisher et al.*, 1986], but solvable to optimality for small instances. There are a large range of methods that have been applied for finding near optimal solutions to models like the generalized assignment problem in the presence of additional constraints [e.g., *Osman*, 1995; *Laguna et al.*, 1995].

[52] To accommodate the different decision variables (x_i^m, h_l^m, y_i) for operations of regulators/weirs and investments we applied a 2-stage recursive heuristic method that exploits this structure. Two-stage or nested methods are suitable for solving problems with more than one type of decision variable. To avoid solving a P-median problem for y_i and reduce the amount of solution method nesting, we can solve for y_i implicitly. This is done by solving for x_i^m assuming all regulated wetland complexes are available, and enforcing the budget constraint (1) to limit the number of new ones used. The solution method is best described using the following algorithm:

[53] Algorithm 1
Set the decision variables X^{best}, H^{best}, $Z^{best} = 0$
Initialise $X = 0$, $H =$ midpoint weir heights
Repeat
Solve for X using Algorithm 2
Solve for H using Algorithm 3
UNTIL There is no further improvement in the solution

[54] There are a wide range of suitable meta-heuristics for solving the subproblems for x_i^m and h_l^m, including simulated annealing and tabu search [*Osman*, 1995; *Higgins*, 2001], genetic algorithms [*Chu and Beasley*, 1996], and hybrid heuristics [*Amini and Racer*, 1995]. Any of these methods could have been applied and a comparison between methods is beyond the scope of this paper. An important consideration was that the selected method needed to have fast convergence, particularly as the subproblems needed to be repeatedly solved for x_i^m and h_l^m. In this study, we used the tabu search method.

[55] The general tabu search heuristic is based on the establishment of moves so as to transform a current solution to a neighboring solution. The tabu search escapes local optimal solutions by allowing up-hill (nonimproving) moves to be performed when no down-hill (improving) moves are available. At each iteration of the tabu search, the neighborhood (or a sample of it) is explored. The best nontabu move found in the search is applied. A move is tabu if it is one of the *TL* (tabu list) most-recent moves implemented. If this tabu list size *TL* is too small, the heuristic will cycle through a series of solutions. The tabu status is over-ridden if the solution satisfies an aspiration criteria function. Four neighborhoods are applied, two for each of the decision variables:

[56] Neighborhood 1
Open or close the regulator(s) in a wetland complex. If $x_i^m = 1$, then let $x_i^m = 0$. If $x_i^m = 0$, then let $x_i^m = 1$.

[57] Neighborhood 2
Open regulator(s) in one complex and close another. If $x_i^m = 1$ and $x_{i'}^{m'} = 0$ then let $x_i^m = 0$ and $x_{i'}^{m'} = 1$.

[58] Neighborhood 3
Raise or lower a weir. If $h_l^m = wh1$, then let $h_l^m = wh2$, where $wh1, wh2 \in WH$.

[59] Neighborhood 4
Raise one weir and lower another. If $h_l^m = wh1$ and $h_{l'}^{m'} = wh2$ then let $h_l^m = wh2$ and $h_{l'}^{m'} = wh1$.

[60] The two neighborhoods for each of the decision variables, x_i^m and h_l^m, complement one another during the tabu search routine. Neighborhoods 2 and 4 are applied more frequently when it is difficult to improve the solution due to constraints (1) and (4). After ϕ' continuous iterations where the best solution is not improved, the search is intensified by replacing the current solution with the best so far. The tabu search strategies used are described by Algorithms 2 and 3.

[61] Algorithm 2
Set $\phi = 0$
Let $Z' = Z$, $Z^i = Z$, $X' = X$, $X^i = X$,
REPEAT
Repeat
Obtain a sample of moves from neighborhoods 1 and 2 of X', and let X be the move in the sample that produced the maximum objective function value Z.
IF $Z < Z'$ and the move is not tabu and constraints (1) to (10) are satisfied, SET $Z' = Z$, $X' = X$
IF $Z < Z^i$ SET $Z^i = Z$, $Z' = Z$, $X' = X$, $X^i = X$, $\phi = 0$
UPDATE the tabu list with the reverse move
ADD 1 To ϕ
UNTIL $\phi = \phi$
$Z' = Z^i$, $X' = X^i$
UNTIL convergence criteria is achieved

[62] Algorithm 3
Set $\phi = 0$
Let $Z' = Z$, $Z^i = Z$, $H' = H$, $H^i = H$.
REPEAT
Repeat
Obtain a sample of moves from neighborhoods 3 and 4 of H' and let H be the move in the sample that produced the maximum objective function value Z.
IF $Z < Z'$ and the move is not tabu and constraints (1) to (10) are satisfied, SET $Z' = Z$, $H' = H$
IF $Z < Z^i$ SET $Z^i = Z$, $Z' = Z$, $H' = H$, $H^i = H$, $\phi = 0$
UPDATE the tabu list with the reverse move
ADD 1 To ϕ
UNTIL $\phi = \phi'$
$Z' = Z^i$, $H' = H^i$
UNTIL convergence criteria is achieved

[63] In Algorithm 2, the best values found of ϕ' and the TL were 50 and 15, respectively. We experimented with the neighborhood sample sizes and found the following to work well for Neighborhoods 1 to 4 respectively: 200, 100, 30, 50. The performance of Algorithms 2 and 3 were not sensitive to small changes in the chosen neighborhood sample sizes. An extensive analysis on the calibration of ϕ', TL and the neighborhood sample sizes is beyond the scope of this paper.

4. South Australian River Murray Application

[64] In this section, we demonstrate the capability of the optimization model using River Murray floodplain as a case study (Figures 2 and 3). The case study area encompasses the lower reaches of the River Murray in South Australia (Figure 2). In the study area the river runs through semiarid to Mediterranean agricultural land and flow is regulated by 6 weirs (referred to as locks 1–6) which supply irrigation water. In addition, multiple existing regulators control flows in individual wetlands to achieve ecological and water savings objectives.

[65] Major floodplain 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 section 1.

[66] The River Murray case study contained 9280 individual water course, floodplain, and wetland polygons along the 650-km portion of the river in South Australia (Figure 2), identified from vegetation survey and mapping. These were classified into 18 ecohydrological types based on vegetation mapping and commence-to-fill flow values [*Overton et al.*, 2009]. A total of 16 ecological components were identified for the study area including vegetation assemblages, water bird habitat, and fish assemblages. Eleven of these included separate response functions for adult and juvenile life stages totalling 27 individual response functions [*Overton et al.*, 2010]. In the Murray Flow Assessment Tool (MFAT), *Young et al.* [2003] synthesized response functions for several ecological components in nine zones along the River Murray and its tributaries. These formed the basis for our functions. Several of these ecological response functions were updated with information from *Overton et al.* [2009] and *Ecological Associates* [2010], as well as expert opinion. We refer the reader to *Overton et al.* [2010] and *Bryan et al.* [2010] for a detailed explanation of the derivation of ecological response functions.

[67] Six weirs are located along the river with an operating height range of −50 cm to 50 cm. In the study area, modeled weir heights are set at increments between −30 cm and 50 cm, $WH = \{-30,-25,-20,-15,-10,-5,0,5,10,15,20,25,30,40,50 \text{ cm}\}$. With advice from the water utility, SA Water, we formulated values $bm = 30$ cm, $bw = 50$ cm for maximum change within a month and maximum difference between neighboring weirs, respectively.

[68] A total of 357 individual wetlands can be grouped into 125 wetland complexes, of which 43 are already regulated, leaving 82 eligible for investment in our model. We identified the optimal sites for regulators in each of these wetland complexes using a combination of LiDAR elevation data, high resolution orthophotography, and spatial data layers. We also identified irrigation pump and pipeline infrastructure required for each complex. We calculated the upfront costs of regulator and pump relocation infrastructure

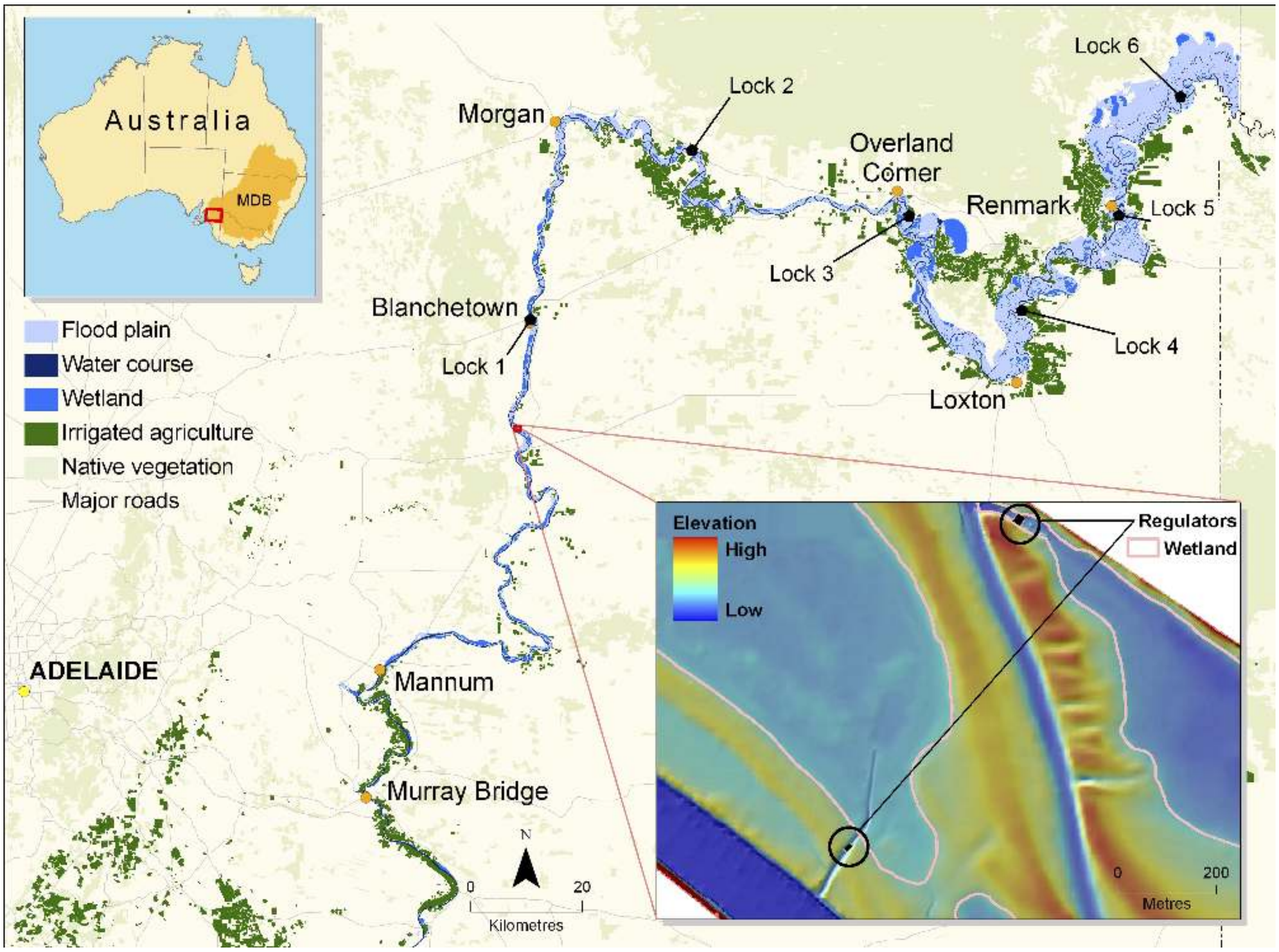

Figure 2. Study area of the South Australia River Murray showing the location of the weirs. The zoomed insert illustrates, for a small section of the river, LIDAR-derived, high resolution topographic information used to delineate the location of regulators in the flood plain.

required in the each of these 82 wetland complexes (including moving irrigation pumps from wetlands). For the case study in this paper we applied a total budget of AUD60 million. A planning horizon of 20 years was used for the analysis, with the natural and current hydrographs of 1986 to 2006. This will accommodate some climate variability of dry and wet years, though a longer hydrograph (e.g., 100 years) can be used to accommodate changes in the environment or climate. The River Murray Floodplain Inundation Model (RiM-FIM) [*Overton*, 2005] was used to quantify the spatial distribution of inundation of ecohydrological polygons based on the hydrograph dynamics. The 1986–2006 hydrographs are shown in Figure 4, and highlight the seasonal and annual variability in flow. The current hydrograph has less water than the natural since over 50% of the water is extracted upstream for agricultural purposes. These hydrographs were used to calculate r^m, p^m.

[69] The model, including Algorithms 1 to 3, were coded using Lahey Fortran 95 on a PC with dual core 2.1 GHz processor and 4 Gigabytes of RAM. Figure 5 shows the

Figure 3. Part of the study area illustrating the spatial distribution of and relationship between eco-hydrological polygons, wetland complexes, weirs, and regulators. Each eco-hydrological polygon is a discrete and homogeneous spatial unit of a distinct eco-hydrological type. The existence of each ecological component within each eco-hydrological type was specified based on vegetation survey data and expert knowledge [*Overton et al.*, 2010]. Individual wetlands are a special type of eco-hydrological unit whose inundation regimes can be controlled through installing a regulator. Connected individual wetland polygons are grouped into complexes. Complexes comprise distinct investment units because it is impossible to control the inundation regime in part of the complex without investing in all regulators on all wetlands within the complex. Hence, investment is made in either all infrastructure in a complex, or in none at all. Weirs can influence inundation in the weir pool as water accumulated behind the weir floods a specific area. Higher flows as defined by the hydrograph also flood a given spatial area of the floodplain as defined by the RiM-FIM model [*Overton*, 2005, 2010; *Bryan et al.*, 2010].

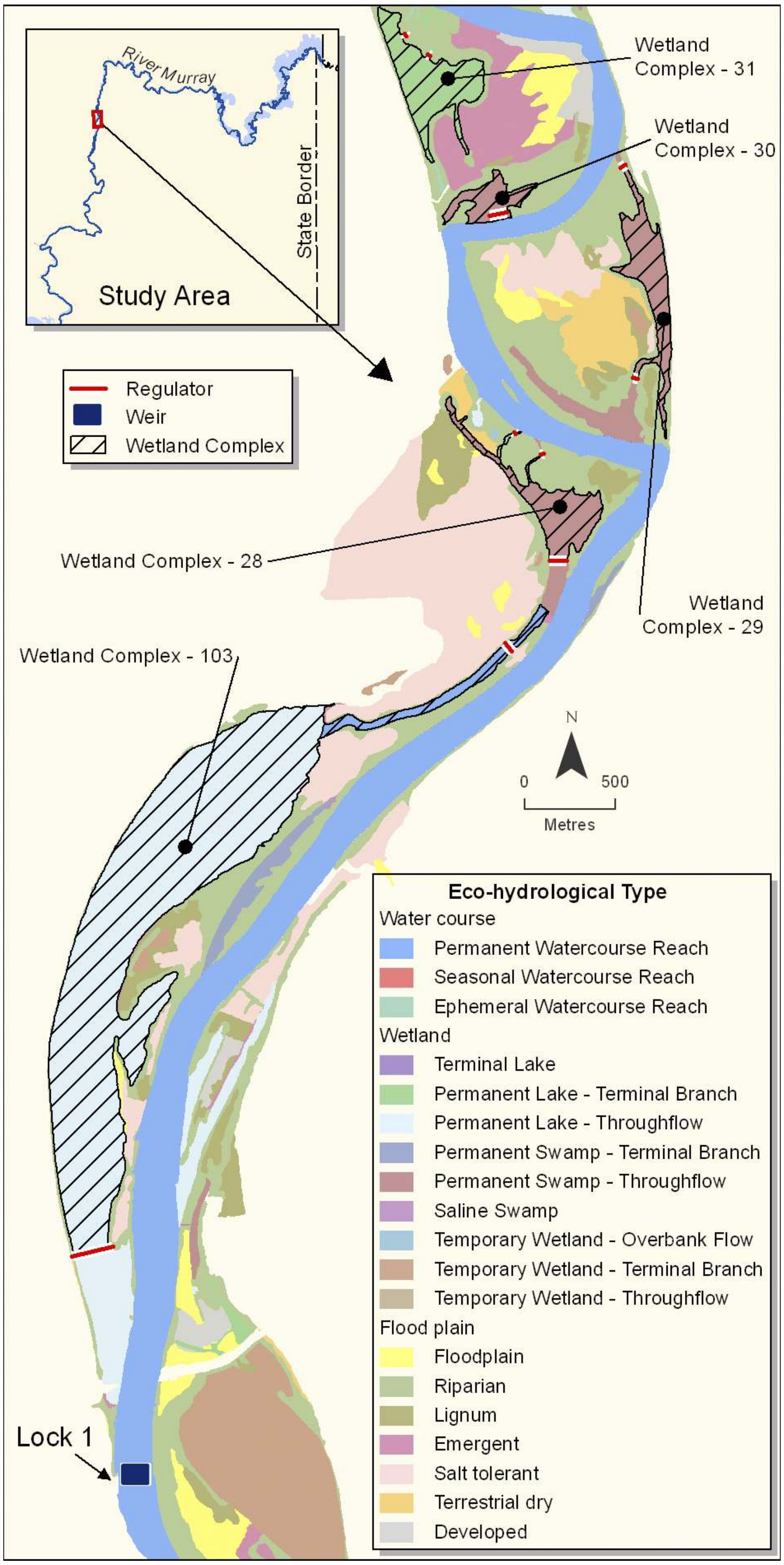
River Murray
State Border
Study Area
Regulator
Weir
Wetland Complex
Wetland Complex - 31
Wetland Complex - 30
Wetland Complex - 28
Wetland Complex - 29
Wetland Complex - 103
N
0
500
Metres
Lock 1
Eco-hydrological Type
Water course
Permanent Watercourse Reach
Seasonal Watercourse Reach
Ephemeral Watercourse Reach
Wetland
Terminal Lake
Permanent Lake - Terminal Branch
Permanent Lake - Throughflow
Permanent Swamp - Terminal Branch
Permanent Swamp - Throughflow
Saline Swamp
Temporary Wetland - Overbank Flow
Temporary Wetland - Terminal Branch
Temporary Wetland - Throughflow
Flood plain
Floodplain
Riparian
Lignum
Emergent
Salt tolerant
Terrestrial dry
Developed

Figure 3

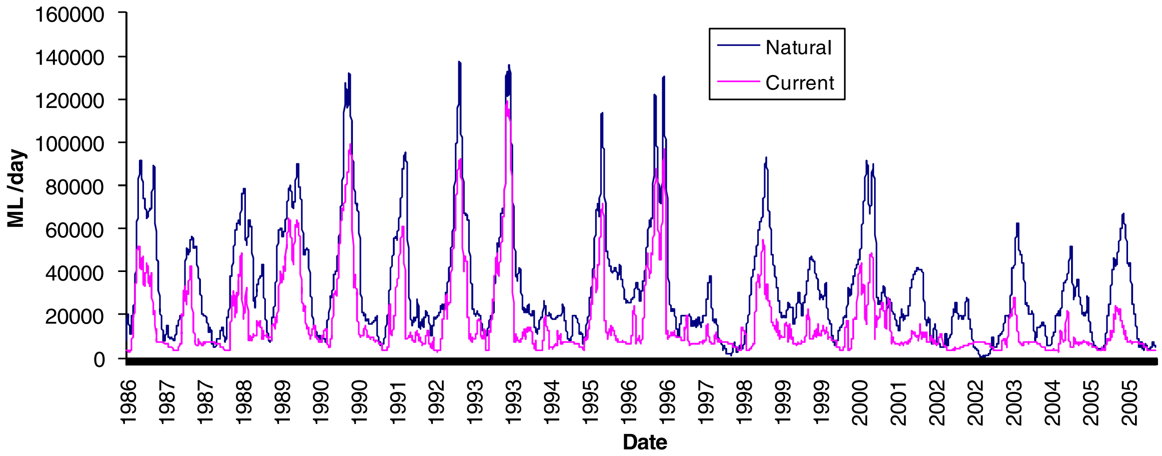

Figure 4. Hydrographs used in the case study showing the modelled natural (predevelopment) flow and modelled flow under current water allocation rules for the period 1986 to 2006.

convergence characteristics when the model was run 10 times with a CPU time of 6 h. It shows that for less than 2 h of CPU time there is a large difference between the high and low solutions. This difference reduces significantly for CPU time between 2 and 5 h. The graph also suggests that a significant amount of further convergence may be achievable for CPU times of much greater than 6 h (e.g., 24 h).

[70] Between 47 and 55 new regulators, out of the 82 eligible locations, were selected (depending on the model run) when a budget of AUD60 million was used. That is, about 60% of the eligible regulators were selected when the funding available was about 50% of the cost of building all regulator complexes. Figure 6 presents an example of weir operation for a solution produced by the model, where Weir (lock) 1 is closest to Adelaide (Figure 2) and Weir 6 is closest to the South Australian border. While only 5 of the 20 years are shown, the solution does illustrate the seasonal operation of the weirs as part of timing of flooding that best replicates natural habitat conditions for the ecological components modeled. All solutions

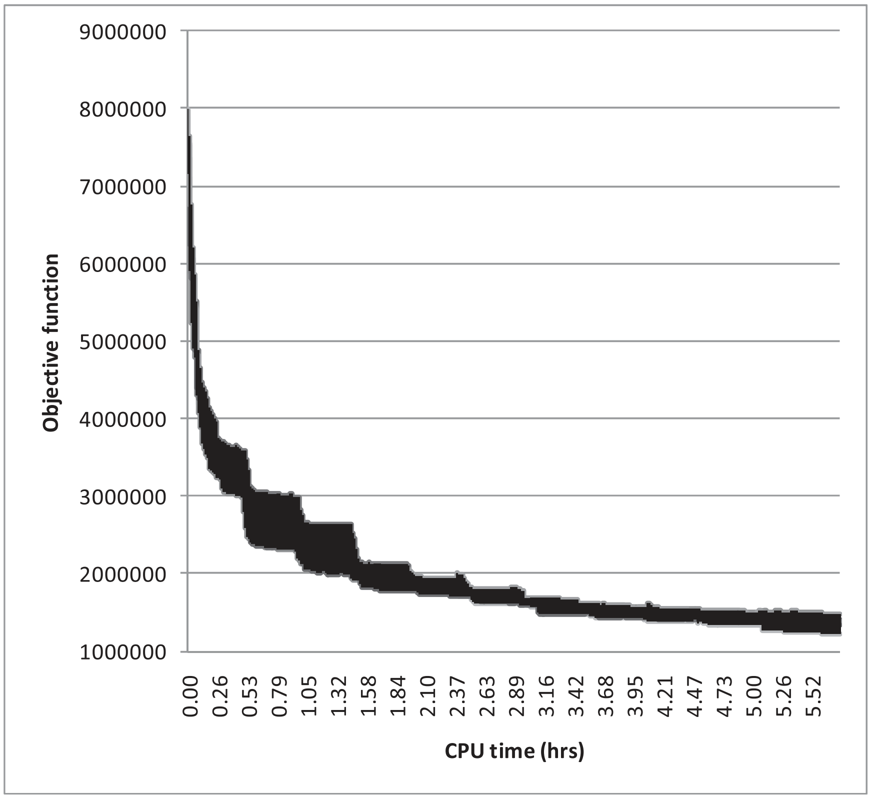

Figure 5. Convergence characteristics of multiple model runs.

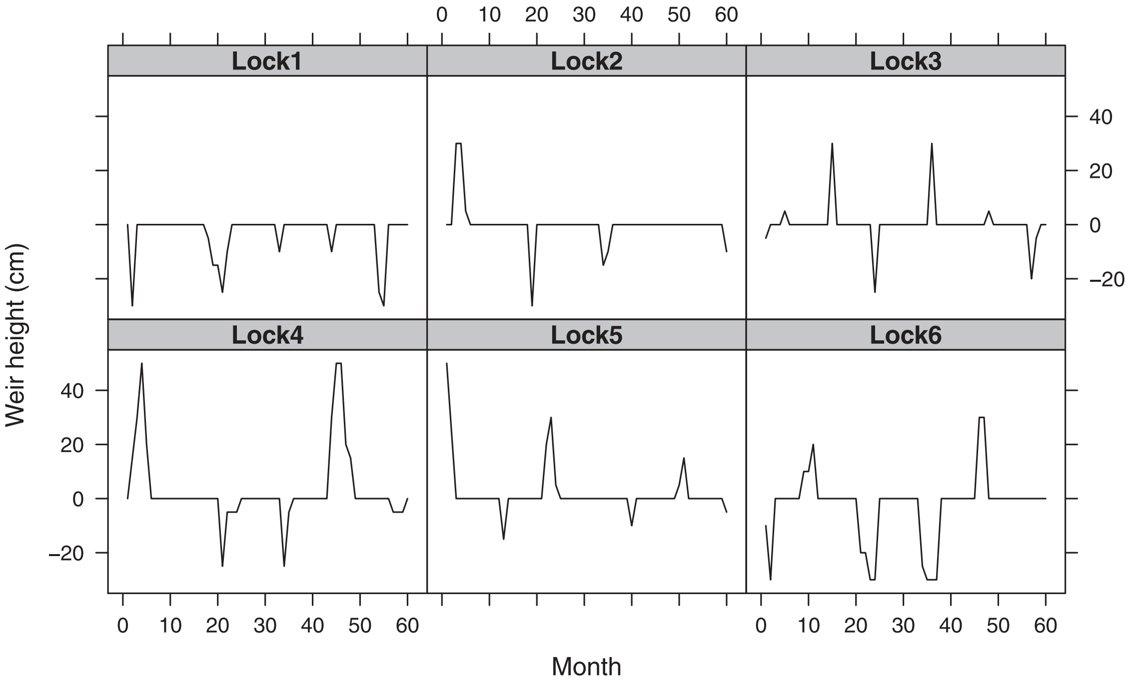

Figure 6. Sample solution of weir operations (see Figure 2 for weir location), for each of the 6 weirs (locks 1–6). The first 60 months of the solution are shown.

produced by the model displayed these seasonal trends of weir operations. Operation of the regulators for each wetland complex did not follow the same seasonality as with weirs, and there were significant differences in the regulator operations for each wetland complex. This result was not unexpected due to the large variety of ecological components across the wetlands (compared to flood plains), each having different desirable FT, FD, and IP characteristics.

[71] Outputs from the model also include indicators for ecological response as per equations (7)–(11). A sample output in Table 1 shows the FD ecological response for a 'do-nothing' solution (i.e., assume no flow control infrastructure) based on the current hydrograph "Base", versus model solution based on the current hydrograph "Model", versus that of a natural hydrograph "Natural". The second column is the ecological health response as a value from 0 to 1. While the model solution cannot achieve the same number of hectares for suitable FD months compared to the natural hydrograph, the objective is to achieve a distribution across the months as close as possible, weighted by the ecological health response. Table 1 shows that the model has achieved an improvement in the number of hectares in suitable FD months (e.g., months 2–5) compared to the Base scenario. The model produced outputs such as Table 1 for each ecological component by weir (lock) for the FT, FD, IP indicators. Summarized ecological scores were generated for each ecological component category by FT, FD, and IP. The values in Table 2 represent the summarized scores for the Model (where the 16 ecological components are grouped into 4 broad categories for illustration), which is an aggregation of values in Table 1 over all ecological functions and river reaches (i.e., between locks). Instead of showing the aggregated scores for Base, Model and Natural, results in Table 2 represent the values for the Model in terms of distance between 0 (Base) and 1 (Natural). The closer the value is to 1 the better. A negative score means that the Model produced a weaker response than the Base

Table 1. Sample Comparison of Solutions: Ecological Health Response for Flood Duration in Flood Spawning Fish[a]

Month	Ecological Health Response	Lock 1			Lock 2		
		Base	Model	Natural	Base	Model	Natural
1	0.1	186	159	77	62	47	44
2	1.0	132	154	226	65	77	197
3	0.9	104	94	90	40	44	108
4	0.8	136	143	203	88	92	135
5	0.7	93	110	157	33	45	67
6	0.6	113	100	171	44	47	100
7	0.6	88	92	161	37	51	66
8	0.5	29	38	92	10	485	507
9	0.4	22	28	43	6	22	17
10	0.3	12	28	36	1	13	11
11	0.2	22	19	11	477	4	5
12	0.2	28	20	4	481	9	0

[a]The ecological health response is measured in hectares.

Table 2. Summarized Ecological Suitability Score of the Model as a Distance Between Base (0) and Natural (1) for Each Grouped Ecological Component Category

	Terrestrial Vegetation	Aquatic Vegetation	Bird Habitat	Fish
FT	−0.006	0.103	0.016	0.046
IP	0.026	0.072	0.011	0.065
FD	0.217	0.541	0.401	0.507

solution for that category. By operating the flow control infrastructure, the Model produced significant improvements in FD compared to the FT and IP indicators. This is not surprising since regulators are an effective means of holding water in, or out of (i.e., for wetlands that are currently flooded more frequently than would have occurred naturally), wetlands to achieve better FD responses. To substantially improve FT and IP we would need to be able to strategically modify the hydrograph which means operating storages and changing water entitlement agreements. This is an area of ongoing research.

5. Discussion and Conclusion

[72] Water resources are becoming increasingly scarce and subject to greater demands from consumptive use. Achieving better ecological health outcomes for highly stressed, regulated rivers such as the South Australian River Murray requires consideration of how features of the natural environmental flows of river ecosystems can be returned through the management of existing and new flow-control infrastructure. The literature to date has primarily focused on reservoir releases [e.g., *Schluter et al.*, 2005; *Richter and Thomas*, 2003; *Tu et al.*, 2003; *Cardwell et al.*, 1996] or the operation of a single weir [*Debecker et al.*, 2006; *Shiau and Wu*, 2007] to achieve these outcomes. We have shown that there is an opportunity to optimally simultaneously manage multiple forms of flow-control infrastructure such as weirs and regulators to improve ecological outcomes.

[73] In this paper we have responded to the call by *Arthington et al.* [2010] for models to better capture the process complexity of environmental flow requirements of river ecosystems. However, this spatial and temporal complexity of environmental flows is a major barrier to the widespread adoption of modeling approaches. We formulated our model as a large nonlinear integer programming problem. Unlike many ecological conservation planning issues that could be formulated as a common problem such as the set-covering or knapsack problem, our model included spatial and temporal dependencies. This presents challenges for real-world implementation. For our South Australian River Murray case study, it was well beyond the capability of commercial software packages for nonlinear integer programming, and cannot be solved to optimality on a standard PC. We showed that state-of-the art meta-heuristics, such as tabu search, converge to good solutions when implemented using a fast programming language such as Fortran. When sufficient CPU time is used, these solutions were able to identify investment strategies leading to significant ecological benefits. We found mathematical programming to be an effective tool to consider the complex interactions of infrastructure investment and the simultaneous optimal operation of flow-control infrastructure, while driving the system toward desirable ecological outcomes. The model also addressed the real-world planning question of how to select a cost-effective suite of investments in establishing new flow-control infrastructure given a limited budget.

[74] The scope of the model can be broadened by a range of extensions to the problem formulations. By relaxing the constraint on fixed total water availability during each month, the timing of storage and release of water along the main river channel can also be optimized. Water released from the ecohydrological polygons into the river system can be used downstream and can have implications on the hydrograph. Additionally, the raising and lowering of the weirs can also influence the downstream shape of the hydrograph and thereby influence ecological responses. The use of multiple hydrograph scenarios (e.g., 20 year blocks from 1906 to 2006) will be important to assessing the sensitivity of infrastructure investments and operations to uncertainty in hydrological conditions. An assessment of the impact of climate change is also important for supporting investment decisions and future river operations that are robust and adaptive to changes in water resource availability. These features will be accommodated in a future version of the model, which may lead to additional model complexity and require refinements to the current solution method. A further extension will be to test and benchmark other solution methods on different size model instances.

[75] The quality of the model can also be enhanced in several ways. The inclusion of a more comprehensive suite of hydrological indicators (e.g., rates of change), improved ecological response functions, and ways of combining these beyond the multiplicative least squares approach may lead to improvements in our estimates of ecological benefits of environmental flows. A detailed analysis and exploration of the sensitivity of the model to variation in input parameters, data, alternative constraints and objective functions is also required to understand the impact on investment and management decisions. We also plan to include a range of other social and economic values in the optimization. The model may be extended to guide the investment and management of water resources to maximize ecosystem service values and to include a range of other costs including those associated with ongoing operation and maintenance. Further, optimization of flow dynamics over space and time should be considered with agricultural demand and optimized such that the benefits are maximized for both agricultural and environmental purposes.

[76] The model presented in this paper as applied in the South Australian River Murray is being used to directly inform decisions under the AUD 110 million Murray Futures Riverine Recovery project, part of the AUD 13 billion Australian Government Water for the Future program. The model will provide decision-makers with a list of the most cost-effective investments in the regulation of flow in specific wetland complexes. The model will also provide managers with a specific month-by-month tactical plan for operating weirs and regulators to maximize the ecological benefit of available flows.

[77] Overall, we have provided an adaptable modeling capability that not only allows the location and operation of flow control infrastructure to be optimized, but allows decision-makers to evaluate different investment options to improve the health of multiple ecological components. The paper makes a significant contribution to decision support for the cost-effective investment in water resources management and the efficient operation of multiple elements of flow control infrastructure. The paper also makes a significant contribution in the use of meta-heuristics for the efficient solution of a very complex nonlinear problem of environmental flow allocation in regulated river ecosystems

with spatial and temporal dependencies. The integration of hydrological, ecological and economic information in a mathematical programming model was essential for identifying cost-effective solutions for managing the health of complex river ecosystems so they can continue producing the many services that society benefits from.

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