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Scenarios involving future climate and water extraction: ecosystem states in the estuary of Australia’s largest river

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Abstract. Management of natural resources, particularly water, increasingly requires that likely benefits of particular actions (e.g., allocating an environmental flow) are quantified in advance. Therefore, new techniques are required that enable those potential benefits to be objectively compared among competing options for management (e.g., compared to a “do nothing” scenario). Scenario modeling is one method for developing such an objective comparison. We used existing hydrologic, hydrodynamic, and ecosystem response models for a case study location, the Coorong, an inverse estuary in South Australia, to illustrate the potential for such scenario modeling to inform natural resource management. We modeled a set of 12 scenarios that included different levels of water extraction, potential future climate change, and sea-level change, thereby enabling a comparison of the different drivers of possible future reductions in water availability in the Coorong. We discovered that potential future climate change combined with current extraction levels has the capacity to devastate the ecology of the Coorong, but also that much of the degradation could be averted by reducing upstream extractions of water. The inclusion of possible sea-level change had a surprising effect, whereby higher sea levels increased hydrodynamic connectivity between the Coorong’s two lagoons. Increased hydrodynamic connectivity limited the occurrence of extremely low water levels and high salinities due to evapoconcentration that were simulated for dry future climates in the absence of sea-level rise. These findings strongly suggest that future ecological degradation in the Coorong is not a foregone conclusion, and that management decisions regarding water allocations upstream will determine the ecological future of this coastal lagoon.

Key words: climate change; Coorong, Australia; environmental conditions; environmental management options; inverse estuary; Murray-Darling Basin; Ramsar Wetland of International Importance; water allocation; water-dependent ecosystem.

INTRODUCTION

Increasingly, natural resource managers are expected to demonstrate the efficacy of an action in advance, in order to secure approvals and funding to undertake that action. Management of water resources, in particular, is difficult due to many competing demands on any amount of available water, with the environment often losing out to human demands from irrigation, domestic uses, stock needs, and industry (Schlüter et al. 2006, Lund et al. 2010, Poff et al. 2010, Kingsford et al. 2011). Thus, managers need to be very clear about what ecological effects are likely to occur from remedial actions to secure water for environmental purposes. Meeting increasing demands for consumptive water use, while maintaining ecological integrity, is a challenge that natural resource managers must face (Schlüter et al. 2006). The management of large-scale ecosystems, such as a whole river basin, is inherently complex and so it is imperative to objectively assess the likely ecological consequences of various management decisions (Schlüter et al. 2006, Powell 2008, Poff et al. 2010). This complexity is compounded with additional uncertainty arising from future climate change. Nevertheless, decisions about how to adaptively manage ecosystems must still be made (Schlüter et al. 2006, Sutherland 2006, Zweig and Kitchens 2010).

Ecosystem response modeling is a tool that shows significant promise in providing managers with objective assessments of competing management options (Saintilan and Overton 2010). One of the key barriers to a greater use of ecosystem response modeling by managers has been the level of complexity of such models, and thus, some understandable reluctance on behalf of river managers to adopt a technique that is difficult to understand, communicate, and implement (Lester et al. 2011). There is also generally a hierarchy of decreasing precision and confidence when moving from models of physical components of the environment to incorporate...
biological and ecological variability (e.g., see Wickle 2003 for a list of uncertainties common in ecological data sets), as well as errors that compound across chained models (Aldous et al. 2011, Lester et al. 2011). Thus, confidence in model outcomes may also erode along this continuum. Despite this, it remains important to explicitly model ecological response when evaluating alternatives that are designed to improve ecological condition, for example, because that ecological response is often shaped by the landscape setting as well as the identities of the organisms living there (Petts 2009). For example, it has long been recognized (Petts 1996) in the determination of environmental flow allocations that there is a need to explicitly link ecological response to hydrology and changes in habitat in order to obtain ecologically sound environmental flow regimes. Links between hydrology and ecology are not necessarily linear, and so understanding the physicochemical impact of a particular management action, for example, is not necessarily sufficient to understand its ecological impact (Petts 2009, Fairweather and Lester 2010). Therefore, available tools that are both relevant and ecologically specific should be used for management planning where possible.

Typically, there are some aspects of an ecosystem that are well studied, and thus understood, but others that are less well known. A key decision when modeling any ecosystem revolves around the delineation of biotic assemblages and their associations with the physicochemical environment. Most ecosystem response models have focused on a few “key” taxa (often vertebrates or flowering plants) and so inferences are based on these taxa acting as surrogates for much of the remaining ecosystem (e.g., Arthington et al. 2006, Poff et al. 2010). In some instances, ecosystem-scale models have been attempted by chaining multiple taxon-specific models to combine predictions across taxonomic groups (e.g., using habitat preference curves for each; Ahmadi-Nedushan et al. 2006). Ecosystem-scale models have also been attempted using the natural associations between suites of co-occurring biota and the physicochemical conditions associated with each suite (e.g., Lester and Fairweather 2011). Determining whether a taxon-specific or ecosystem-wide modeling approach is most suitable will depend, in part, on the management objectives, and the ecological data and understanding available for the region of interest.

Scientists and managers alike also need to understand the potential future impacts within a region in the long term (especially under climate change) to understand how best to safeguard the ecological benefits for an ecosystem via management decisions made now. Many regional systems now have down-scaled climate projections (e.g., Chiew et al. 2008), and so we can proceed with planning for the future. In many regions these forecasts can be linked to river models, thus providing flow estimates under a wide range of future conditions (Chiew et al. 2008). These estimates can then be used to simulate the impact of a range of future stressors on an aquatic ecosystem.

Scenario modeling is one method for objectively comparing the potential outcomes of future stressors, or future management actions, based on the best available understanding of how the system operates (Sutherland 2006). This approach allows for the interactions between environmental systems and human activities to be explored explicitly (Schlüter and Pahl-Wostl 2007) when used to model ecosystem responses. Scenario modeling does not provide predictions of the future, but rather a range of possible alternatives without necessarily assessing the likelihood of each (Sutherland 2006). There have been several recent attempts to model scenarios for regional water-based ecosystems; for example: Schlüter et al. (2006) adopted a modeling approach in the Aral Sea Basin that explored water allocation options, landscape responses to water, and a fuzzy habitat suitability index; Adler (2008) did so for sand movement modeling in the Colorado River; Powell (2008) simulated the water available for different uses under several climatic scenarios (also in the Colorado River); Zweig and Kitchens (2009) modeled succession and disturbance in Everglades wetlands under a range of management and hydrologic scenarios; and Lund et al. (2010) modeled salinity in the delta of the Sacramento-San Joaquin Valley. Previously, we (see Lester et al. 2011) adopted an explicit approach of chaining different sorts of models together to create an ecosystem response model, which has various advantages (e.g., repeatability) and disadvantages (e.g., uncertain propagation of errors across models). In general, there is no single best way to approach the modeling of water-dependent ecosystems and further development of past methods is needed to evaluate what might work best and where.

To add to this body of knowledge, we used a case study region, the Murray-Darling Basin (MDB) to further explore the use of scenario modeling of ecosystem responses as a tool to assist in the assessment of possible future management options. The MDB is Australia’s largest river system and terminates on the South Australian coast in a coastal lagoon complex called the Coorong (Kingsford et al. 2011). The Coorong is part of a Ramsar Convention-listed Wetland of International Importance because the region has substantial cultural, economic, recreation, and environmental values, but these have been eroded because of over-allocation of water upstream and recent drought (Brookes et al. 2009, Kingsford et al. 2011; see Plate 1). The Coorong is an ideal case study to explore possible future scenarios for a region using chained predictive models (Lester et al. 2011) because of the observed decline in condition, the ecological importance of the region (recognized nationally and internationally; Brookes et al. 2009, Kingsford et al. 2011), the desire to provide a good scientific basis to guide the management of the system, its relatively well-studied
nature, and the existence of local hydrodynamic (Webster 2010, 2011) and ecological response (Lester and Fairweather 2011) models demonstrating a clear link between the physical habitat and ecology of the region.

The aims of this research were to develop further such models into a predictive model framework for use in scenario modeling of ecosystem response and to illustrate the utility of that framework for a range of realistic scenarios. Hence, we attempted to predict possible future ecological responses to management actions and climate change via exploring a series of scenarios chosen to cover an array of futures both climatically and in terms of possible management options. These scenarios were developed to answer the following questions: (1) In the absence of water extractions, what is the likely impact of climate change on the hydrology and ecology of the Coorong? (2) Do water extractions and climate change interact either synergistically or antagonistically to influence the hydrological and ecological conditions of the Coorong? (3) Do changes in sea level (sea-level change; hereafter SLC) associated with climate change alter the impact on the hydrology and ecology of the Coorong?

Based on these scenario simulations, we describe some possible implications for managing the Coorong, an inverse estuary in South Australia, as our case study region.

**Methods**

**Study region**

The Coorong (see map in Appendix A) is separated from the Southern Ocean by a narrow sand peninsula and artificially divided from the freshwater Lakes Alexandrina and Albert to the north by a series of barrages completed in about 1940 (Kingsford et al. 2011). The barrages include gates that can be opened to allow the passage of freshwater into the Coorong. The Coorong behaves as an inverse estuary in which the excess of evaporation over precipitation drives an inward flow of seawater away from its connection to the ocean (sensu Wolanski 1987). This process tends to accumulate salt within the Coorong, but oscillatory currents driven by winds and by local sea-level variations penetrating into the lagoon via the Mouth channel act to mix this salt back toward the sea. The resulting balance between mixing and evaporation causes the salinity to increase toward the distal end (from the sea) of the Coorong.

Flows over the barrages affect Coorong hydrodynamics in three main ways. First, they scour the Murray Mouth channel seasonally, allowing sea-level variations to penetrate into the Coorong and facilitate the along-lagoon mixing that lowers salinity (Webster 2010). Then, barrage flows freshen the North Lagoon, resulting in estuarine water being drawn along the Coorong to replace evaporative losses. Finally, due to flow constriction at the mouth, springtime barrage flows cause a rise in water level along the length of the Coorong that significantly augments and extends rises that are due to seasonal sea-level variation. This seasonal water level variation facilitates salt loss from the South Lagoon.

The Coorong can be divided into three regions: Northwest of the Murray Mouth to the southern limit of the barrages is the Murray Mouth Estuary region, and the other two regions are the North and South Lagoons, which are divided by a constricted channel near Parnka Point (see Appendix A). Hypersaline conditions are usual in the South Lagoon. The estuary region typically fluctuates between zero when barrages are flowing and seawater salinity when they are not. The North Lagoon represents a transition region between the estuary region and the South Lagoon.

**Hydrodynamic and ecosystem states model descriptions**

A one-dimensional hydrodynamic model simulates water levels and salinities (Webster 2010) from the Murray Mouth south, including most of the estuary region and the North and South Lagoons. The model is forced by sea levels, wind, barrage flows, evaporation, precipitation, tidal exchange, and additional freshwater inflows at the southern end of the Coorong at Salt Creek (Appendix A). Validation indicated that the model was well able to represent the time series of measured water levels and salinities (Webster 2010). This lends credibility to conclusions drawn from model applications about the dynamics of the Coorong.

In order to assess ecological condition in the Coorong, an ecosystem response model based on “ecosystem states” was also developed (Appendix B; Lester and Fairweather 2011). It is a data-derived state-and-transition model (Bestelmeyer et al. 2004, Briske et al. 2005), based on relationships between the biota that occur within the system at any one point in space and time and the environmental conditions under which these biota occur.

The ecosystem states model identified eight ecosystem states (i.e., suites of co-occurring biota; the “states” of the model) and thresholds in physicochemical conditions that separated their occurrence in space and time (see Appendix B). These thresholds (the “transitions”) occurred in variables describing the daily tidal range, length of time with no freshwater flows, and average annual water levels, depths, and salinity (Lester and Fairweather 2011). The combination of conditions across those variables, in a hierarchy reflected by the order in which the variables are listed (see Appendix B), determined which of the eight ecosystem states was simulated for each location in time and space. Locations were based on the 12 focal sites for which data were available (Lester and Fairweather 2010, 2011), and times were described by years in the model simulations (see Scenario analyses). Each location in each year is referred to as a “site-year.” The eight ecosystem states appear to represent two main ecosystem types (i.e., estuarine–marine and hypersaline basins of attraction) and a range in ecological conditions (i.e., from relatively healthy to highly degraded; Appendix B; Lester and Fairweather 2011).
allowing an assessment of the likelihood of ecological degradation to be given for combinations of climate and extraction levels using scenario analyses (e.g., Lester et al. 2011).

The intended use of the ecosystem states model was as a tool to predict the likely ecological consequences of a variety of possible management strategies under a range of climate change simulations. Several changes had to be made to the existing model (Lester and Fairweather 2011) in order to allow it to be used in a predictive fashion. These included extrapolating the results of the hydrodynamic model to other sites within the Coorong (i.e., due to a mismatch in model domains), developing code to run the ecosystem state model using a time series of input data, and further testing to determine the sensitivities of the predictive model. Description of this process and its results are shown in Appendix C.

**Scenario analyses**

In order to assess the likely ecological outcomes from climate change and potential management actions, the predictive model was applied to a set of 12 possible future scenarios for the Coorong (Table 1). For the ecosystem states model, salinity and water level were derived from hydrodynamic model simulations of the Coorong (Webster 2010). The barrage flows used by the hydrodynamics model were based on MDB flows simulated by CSIRO (2008) for each of three future climate scenarios. The first flow time series used the historical climate sequence (i.e., historical climate) and assumed that current extraction levels and water resources infrastructure within the basin were in place for the entirety of the model run (Scenario A in CSIRO [2008]). The second climate scenario (Scenario Cmid in CSIRO [2008]) was the median climate predicted for 2030 derived using the climate sequence for 1891–2008, based on the output of 15 global climate models under three climate change scenarios (i.e., a median future climate), whereas the third climate scenario used the tenth percentile output (Scenario Cdry in CSIRO (2008)) from the 45 climate model runs described above (i.e., a dry future climate). Thus, the three climates progressively simulate longer low-flow and dry periods and longer intervals between floods.

A scenario that simulated River Murray flows in the absence of water infrastructure development in the Basin (i.e., Without Development) was also used (Scenario P in CSIRO (2008)). The Without Development scenario represents conditions that may occur with no extraction from the basin and none of the current infrastructure except the barrages. The Without Development scenario also assumes a time series of inflows via Salt Creek into the South Lagoon that represent the average seasonal cycle measured between 2001 and 2008 (see Appendix A). One scenario excluding development was developed for each of the three climates investigated, and each specifies “Without Development” in the scenario name (Table 1). All other scenarios include current water resources infrastructure and extractions, so should be considered to be effectively “With Development.”

Three scenarios of mean SLC were also modeled, using the addition or subtraction of the extra volume uniformly to mean sea levels (i.e., −10 cm, +20 cm, and +40 cm) in the forcing sequences. These values represent the low, median, and high predicted SLC for the region by 2030 (CSIRO Marine and Atmospheric Research 2008). All scenarios used a 114-year model run, which was the length of the available barrage-flow simulations. These scenarios were grouped into sets and the 12 combinations are shown in Table 1.

For each scenario, a number of analyses were undertaken to characterize the simulated hydrodynamics and ecosystem states. Boxplots (Fig. 1) were

<table>
<thead>
<tr>
<th>Table 1. Summary of the 12 scenarios investigated.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scenario</strong></td>
</tr>
<tr>
<td>Historical climate (benchmarks)</td>
</tr>
<tr>
<td>A) Current Conditions</td>
</tr>
<tr>
<td>B) Without Development</td>
</tr>
<tr>
<td>Effects of climate change to 2030</td>
</tr>
<tr>
<td>C) Median Without Development</td>
</tr>
<tr>
<td>D) Dry Without Development</td>
</tr>
<tr>
<td>E) Median Future</td>
</tr>
<tr>
<td>F) Dry Future</td>
</tr>
<tr>
<td>Effects of sea-level change (SLC)</td>
</tr>
<tr>
<td>G) Median Future, −10 cm SLC</td>
</tr>
<tr>
<td>H) Median Future, +20 cm SLC</td>
</tr>
<tr>
<td>I) Median Future, +40 cm SLC</td>
</tr>
<tr>
<td>J) Dry Future, −10 cm SLC</td>
</tr>
<tr>
<td>K) Dry Future, +20 cm SLC</td>
</tr>
<tr>
<td>L) Dry Future, +40 cm SLC</td>
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</tbody>
</table>

Notes: A “yes” entry denotes being at current levels, and “no” indicates none included within the scenario. Freshwater inputs via Salt Creek (see Appendix A for a map) were average flows between 2001 and 2008 for all scenarios, and no dredging of the Murray Mouth was included in any scenario.
FIG. 1. Boxplots showing the distribution of values for each of the variables driving the ecosystem states of the Coorong, an inverse estuary in South Australia, for all 12 scenarios, which included different levels of water extraction, potential future climate change, and sea-level change. The variables are: (a) water level (m AHD [Australian Height Datum]), (b) water depths from the previous year, (c) salinity, (d) maximum number of days since flow over the barrages, and (e) tidal range. Scenarios are labeled as follows: A, Current Conditions; B, Without Development; C, Median Without Development; D, Dry Without Development; E, Median Future; F, Dry Future; G, Median Future, −10 cm SLC (sea-level change); H, Median Future, +20 cm SLC; I, Median Future, +40 cm SLC; J, Dry Future, −10 cm SLC; K, Dry Future, +20 cm SLC; and L, Dry Future, +40 cm SLC. Bars underneath the scenario labels indicate the groups of scenarios as defined in Table 1. The center line of the boxplots is the median, the top and bottom of the box are the interquartile range, the whiskers are the 95% confidence interval, and outliers are any points outside the 95% confidence interval. Refer to Table 1 for additional definitions.
constructed for each hydrodynamic variable driving ecosystem states (i.e., tidal range, maximum number of days without barrage flow, water level, water depth from the previous year, and salinity), using the R statistical environment (R Development Core Team 2008). Threshold analysis was undertaken for each hydrodynamic variable driving ecosystem states for each scenario (see Appendix D).

A Gini coefficient was calculated and runs analysis undertaken for each hydrodynamic variable for each scenario. Gini coefficients have only recently been applied to ecological problems (Naeem 2009, Wittebolle et al. 2009), but are a measure of evenness of dispersion of a variable. A Gini coefficient is calculated by finding the difference in the area under a curve based on a cumulative distribution (here, of a hydrodynamic variable) and a Lorenz curve (Wittebolle et al. 2009). Values vary between 0 and 1, with 0 representing a perfectly evenly dispersed distribution and 1 representing a completely unevenly dispersed distribution. Runs analyses tested the sequence of states appearing at each site in each scenario (Zar 2010). A runs analysis assesses the significance of a given time series of categorical variables by comparing it to a random time series of the same number of categories. Analyses were conducted in the R statistical environment.

Two additional types of figures were developed to illustrate the output of the individual scenarios. The “cuisinaire plot” (e.g., Fig. 2) compared the proportion of site-years in each ecosystem state for each scenario (see Appendix D). The “vector diagrams” (e.g., Fig. 3) illustrate the deviation of each scenario from the Current Conditions scenario, using four of the five hydrodynamic variables driving the allocation of site-years into the various ecosystem. Each of the 12 scenarios is shown as an individual vector. Within each scenario, individual site-years were divided into those falling into each of the two basins of attraction (i.e., the marine basin where site-years were above the tidal range threshold or the hypersaline basin for the remainder). For those hypersaline-basin site-years, the sum of deviance of each site-year...
from the Current Conditions scenario was calculated for the variables of water level and days without barrage flows. For marine-basin site-years, the sum of deviance was calculated for salinity and days without barrage flows (i.e., in line with the driving variables for the two basins; see Appendix B). For the marine basin, depth in the previous year was also a driving variable, but inspection of scenario results indicated that it was rarely exceeded, so for ease of presentation in two dimensions, this analysis was limited to two variables per basin. Analyses were conducted in the R statistical environment.

The similarity of the mix of ecosystem states simulated for each scenario can be shown using a nonmetric multidimensional scaling ordination plot (e.g., Fig. 4). Each scenario was represented by a single point that is determined by the number of each of 64 possible transitions that occurred over the entire model run. For example, one such possible transition is a movement from the Estuarine/Marine state to the Marine state in the following year. Plotting all scenarios in this manner allows a comparison of how similar each scenario is to all others (by how close the respective points are on the ordination plot) and which have the biggest overall impact on the collective ecosystem states of the Coorong.

**RESULTS**

**Comparing Current and Without Development Conditions**

The effect of current extraction levels on Coorong hydrodynamics was evident when comparing the Without Development scenario to the Current Conditions scenario (Fig. 1). Unsurprisingly, median water levels were higher without current extractions, and remained higher under all fluctuations in climate conditions and the median maximum number of days since flow over the barrages was zero for the Without Development scenario, compared with 135 days for the Current Conditions scenario. Coorong salinities also differed under Without Development conditions, being lower than the interquartile range observed for the Current Conditions scenario 50% of the time, but depths were similar. Finally, the tidal range observed under Without Development conditions was substantially more variable, with a higher proportion of sites experiencing a bigger tidal fluctuation than was observed under the Current Conditions scenario. This indicates that the Murray Mouth would be in a more open state under the Without Development scenario allowing more efficient tidal transmission of seawater into the Coorong.

Threshold analyses also illustrated that the tidal prism extended more reliably into the North Lagoon. All sites except those in the South Lagoon exceeded the threshold for tidal range (Appendix D), while South Lagoon sites showed similar tidal characteristics. The threshold for maximum number of days without flow (i.e., 339 days) and the lower water level threshold (i.e., −0.09 m AHD [Australian Height Datum]) were never exceeded under the Without Development scenario, while the salinity threshold was exceeded only in the last year of the model simulation. The higher water level threshold (i.e., 0.37 m AHD) had a return time for each region that was
approximately half that observed under Current Conditions (e.g., 4.4 years for the Murray Mouth region for Without Development, compared to 8.1 years under Current Conditions).

Gini coefficients indicated that tidal ranges, water levels, and depths were all more evenly distributed for the Without Development scenario than under the Current Conditions scenario (e.g., 0.08 for tidal range under the Without Development scenario compared to 0.16 under Current Conditions; Table 2). Salinity and maximum length of time without flow were more uneven for Without Development conditions (0.30 and 0.84, respectively) compared to Current Conditions (e.g., 0.21 for salinity and 0.46 for length of time without flow), suggesting that extremely high values occurred rarely over the 114-year model run in the absence of extractions and water resource development.

The two most common ecosystem states over the 114-year Current Conditions scenario model run were the Estuarine/Marine state (70% of site-years) and the Average Hypersaline state (20%; Fig. 2). Relatively degraded states (see Appendix B) occurred in 6% of site-years. The two most degraded states, Degraded Marine and Degraded Hypersaline, appeared in 1% of site-years each. This emphasized that the recent drought conditions of the Coorong (2006–2008, for example)

### Table 2. Summary of Gini coefficients calculated for each of the driving variables (shown as means) in the ecosystem state model for all of the scenarios investigated.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Mean tidal range (m)</th>
<th>Maximum days since flow</th>
<th>Mean water level (m AHD)</th>
<th>Mean salinity (g/L)</th>
<th>Mean depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Conditions</td>
<td>0.16</td>
<td>0.46</td>
<td>0.07</td>
<td>0.21</td>
<td>0.04</td>
</tr>
<tr>
<td>Without Development</td>
<td>0.08</td>
<td>0.84</td>
<td>0.05</td>
<td>0.30</td>
<td>0.03</td>
</tr>
<tr>
<td>Median Without Development</td>
<td>0.18</td>
<td>0.43</td>
<td>0.07</td>
<td>0.20</td>
<td>0.04</td>
</tr>
<tr>
<td>Dry Without Development</td>
<td>0.09</td>
<td>0.60</td>
<td>0.06</td>
<td>0.25</td>
<td>0.03</td>
</tr>
<tr>
<td>Median Future</td>
<td>0.17</td>
<td>0.43</td>
<td>0.09</td>
<td>0.20</td>
<td>0.04</td>
</tr>
<tr>
<td>Dry Future</td>
<td>0.20</td>
<td>0.51</td>
<td>0.03</td>
<td>0.17</td>
<td>0.03</td>
</tr>
<tr>
<td>Median Future, −10 cm SLC</td>
<td>0.08</td>
<td>0.78</td>
<td>0.05</td>
<td>0.30</td>
<td>0.03</td>
</tr>
<tr>
<td>Median Future, +20 cm SLC</td>
<td>0.19</td>
<td>0.43</td>
<td>0.04</td>
<td>0.20</td>
<td>0.03</td>
</tr>
<tr>
<td>Median Future, +40 cm SLC</td>
<td>0.20</td>
<td>0.43</td>
<td>0.04</td>
<td>0.19</td>
<td>0.02</td>
</tr>
<tr>
<td>Dry Future, −10 cm SLC</td>
<td>0.20</td>
<td>0.51</td>
<td>0.09</td>
<td>0.19</td>
<td>0.04</td>
</tr>
<tr>
<td>Dry Future, +20 cm SLC</td>
<td>0.21</td>
<td>0.51</td>
<td>0.04</td>
<td>0.16</td>
<td>0.02</td>
</tr>
<tr>
<td>Dry Future, +40 cm SLC</td>
<td>0.21</td>
<td>0.51</td>
<td>0.03</td>
<td>0.07</td>
<td>0.02</td>
</tr>
</tbody>
</table>

**Note:** Gini coefficient values close to 0 indicate an even distribution, and values closer to 1 indicate an uneven distribution. AHD stands for Australian Height Datum.
were quite unusual, even over a 114-year time frame using current extraction levels. Transitions occurred between states for 14% of site-years, with state inertia (i.e., the proportion of site-years where the state did not change) of 86%. The sequence in which the states appeared at each site across the 114 years was significantly different from a random distribution (\(Z_c\) ranged from 3.91 to 7.74, \(P < 0.0001\) for all sites). When transitions did occur, sites changed basin (i.e., went from a marine state to a hypersaline state or vice versa) in 4% of site-years, indicating a shift in the penetration of the tidal prism. When sites changed within the same basin, they shifted to a more degraded state 6% of the time and to a less degraded state 4% of the time.

Under the Without Development scenario, only three of the possible eight ecosystem states occurred (Fig. 2), all of which can be considered healthy (see Appendix B). These were the Estuarine/Marine, Healthy Hypersaline, and Average Hypersaline ecosystem states. The overall change in the proportion of healthy ecosystem states was relatively small (6%), but the mix of site-years within each state also changed, with the Healthy Hypersaline state more common (15% of site-years for Without Development compared to 3% under Current Conditions). To compensate, fewer site-years were classified as the Average Hypersaline state under Without Development conditions (8% under Without Development compared to 20% under Current Conditions). Transitions between states occurred in 11% of site-years, with 8% of the 11% occurring during the final decade. During the entire model run, sites in the Murray Mouth and North Lagoon did not vary from the Estuarine/Marine state. Runs testing showed that the sequence of state changes were not different from a random arrangement for the center of the South Lagoon (i.e., Jack Point, \(Z_c = 0.90, P = 0.184\); see Appendix A for all specific locations), but did have a significant order for both ends of the South Lagoon (i.e., Villa dei Yumpa, \(Z_c = 3.67, P = 0.001\); and Salt Creek, \(Z_c = 3.27, P = 0.004\)).

**Investigating the effect of climate change**

Climate change has the potential to dramatically affect the hydrodynamic drivers of ecosystem states within the Coorong (Fig. 1). The predictions for a median 2030 climate showed an increase in the median number of days without flow over the barrages relative to the Current Conditions scenario. The observed range of maximum salinity values increased by ~34% from 203 to 273 g/L under the Median Future scenario and predictions made under a dry 2030 climate at current extraction levels were extreme. Under the Dry Future scenario, the maximum number of days without flow over the barrages was 2778 days, with a median value of 320 days (or >10 months). Salinity also increased to a median of 60 g/L with a maximum of 461 g/L. The maximum should be considered to be indicative because the effects of increased salinity on evaporation rate and on the volumetric behavior of brine once salinity exceeds ~200 g/L are not accommodated within the model (Webster 2010).

The tidal prism extended a shorter distance into the North Lagoon under increasing levels of climate change and remained over the daily tidal range threshold for shorter periods of time, with longer return intervals (Appendix D). There was an increase in the length of time that the threshold for the maximum number of days without flow was exceeded with climate change, particularly under the Dry Future scenario (1.8, 1.8, and 4.8 years, for the Current Conditions, Median Future, and Dry Future scenarios, respectively), and the likelihood of crossing the lower water level threshold increased. Return intervals for exceeding the higher water level threshold also increased. Under the Dry Future scenario, the South Lagoon always exceeded the salinity threshold (except for the first year of model simulation), and sites in the Murray Mouth region occasionally exceeded the threshold, too.

Gini coefficients were similar between the Median Future and Current Conditions scenarios (Table 2). Differences in coefficients were slightly larger for the Dry Future scenario, with water levels and salinities becoming more evenly distributed and tidal ranges and days without flow becoming less even.

The ecosystem states that were most affected with increasingly severe climate change simulations were the Estuarine/Marine state and the Average Hypersaline state (Fig. 2). The occurrence of the Estuarine/Marine state declined from 70% of site-years under Current Conditions to 66% and 39% under the Median and Dry Future scenarios, respectively. These states were replaced by an increase in the occurrence of Marine, Unhealthy Marine, and Degraded Marine states.

**Investigating the effect of climate change without development**

Comparisons of without-development conditions under each of the modeled future climates brought the extreme values observed above into perspective by illustrating the degree to which the changes predicted by the Median Future and Dry Future scenarios were reliant on the level of extractions upstream within the MDB. While there were changes in the hydrodynamic variables, these were not nearly as substantial as those observed between the Current Conditions, Median Future, and Dry Future scenarios (Fig. 1). All three Without Development flow scenarios were an improvement on the Current Conditions scenario for the number of days without flow, salinity, and water levels, despite simulating increasing levels of climate change.

Under without-development conditions, there was little effect of climate change on the likelihood of crossing the thresholds for tidal range, number of days without flow and the lower water level. The higher water level threshold was influenced by climate change, even under without-development conditions, with shorter durations over the threshold observed both along the
Coorong and with increased levels of climate change (Appendix D). Under without-development conditions for either future climate, the dispersion of distributions were very similar to those observed for the Without Development scenario (Table 2). The number of days without flow was the only variable where the dispersion distribution differed from the Without Development scenario. The Without Development scenario had a Gini coefficient of 0.84, but values of 0.78 and 0.60 were calculated under the Median and Dry Without Development scenarios, respectively. This indicated that extreme values were more common under the latter two scenarios, suggesting occasional long periods without barrage flows were simulated.

The relative impact of current extraction levels compared to climate change was also apparent in the mix of ecosystem states simulated (Fig. 2). The Median Without Development scenario had no site-years in a degraded state, and the Dry Without Development scenario had only 2% of site-years in degraded states (compared to 11% and 46% for the Median Future and Dry Future scenarios, respectively). Overall, the effect of climate change on the mixture of ecosystem states (whether the median or dry projection) was small compared to the effect of current extraction levels combined with climate change.

Investigating the effect of changes in sea level

SLC is another aspect of climate change that has the potential to affect the hydrodynamic properties of the Coorong (Fig. 1). Of the variables investigated, water levels were most affected by SLC. A 10-cm decrease resulted in a drop in water levels relative to the Median and Dry Future predictions, while increasing sea levels resulted in large increases in water levels. Water depths were affected in a similar manner. Changes simulated for the salinities and tidal ranges under the various SLC scenarios were small compared with the Median or Dry Future scenarios. The exception was for median salinity, which rose from 60 g/L for the Dry Future scenario to 79 g/L for the Dry Future +40 cm SLC scenario.

Increased sea levels tended to decrease the amount of time that the sites in the Coorong exceeded the threshold for tidal range, but the differences were relatively small (Appendix D). Water levels were more likely to cross both thresholds with SLC and increased sea levels tended to decrease the proportion of time for which sites were over the salinity threshold.

The dispersion of values for the water level variables showed the largest change among the SLC scenarios. A decline in sea level slightly increased the Gini coefficient (e.g., 0.05 under Median Future compared to 0.09 for the Median Future, −10 cm SLC scenario; Table 2).
Increasing sea level decreased the Gini coefficients for water level under median future climate projections, to 0.04 with 20-cm increases in sea level and 0.035 with 40-cm increases.

The effect of SLC on the ecosystem states was small for site-years in the marine basin (Fig. 2), but there were larger differences in the mixture of states predicted for the hypersaline basin as a result of SLC. Somewhat unexpectedly, a decline in sea level resulted in a more degraded set of ecosystem states, particularly for the Dry Future SLC scenarios. For example, there was a substantial decline in the proportion of sites classified as Healthy Hypersaline (i.e., higher for more extreme sea-level rise, at 16% and 14%, compared to <1% for the Dry Future, −10 cm SLC and Dry Future scenarios), and a large increase in the proportion of Degraded Hypersaline site-years. Similar patterns were observed for scenarios using a median future climate simulation.

A rise in sea level, either by 20 or 40 cm, resulted in an increase in the proportion of site-years in the Healthy Hypersaline state relative to the Median Future or Dry Future scenarios (Fig. 2). This was accompanied by a decline in the proportion of site-years predicted to be in the Average Hypersaline state (i.e., from ~20% from the majority of scenarios to 2% with a 20-cm increase in sea level and 0% for a 40-cm increase).

SLC had very little impact on the level of state inertia observed during the model run. Runs analyses confirmed that the sequence of states appearing was significantly different from a random sequence for all SLC scenarios under both the Median and Dry Future climates (with two exceptions under the Median Future, +20 cm SLC scenario).

Comparison across all scenarios

Comparison of vectors for climate change and without-development scenarios showed that several (~5) were very similar to the Current Conditions scenario (i.e., close to the origin; Fig. 3). Most scenarios had little relative impact on water levels and days without flow within the hypersaline basin, with the largest differences observed under a Dry Future climate (Fig. 3a). The without-development scenarios were the only ones to show improvements in days without flow and both water levels relative to the Current Conditions scenario. A similar pattern emerged for the marine basin, where very few scenarios represented an improvement in both variables (Fig. 3b). These tended to be scenarios involving additional fresh water (i.e., without development in the MDB). The largest negative impact on both days without flow and salinities was seen with the dry future climate scenarios.

For the SLC scenarios, there was substantial deviation in water levels compared to the Current Conditions scenario, with sea-level decreases resulting in lower water levels and sea-level rises in higher water levels. No SLC scenarios “improved” relative to the Current Conditions scenario (e.g., showed both higher water levels and fewer days without flow than the Current Conditions scenario in Fig. 3a). Overall, the effect of SLC was less than the effect of climate change on the evaporation and rainfall.

The similarity of the mix of ecosystem states across scenarios can be shown using a nonmetric multidimensional scaling ordination plot (Fig. 4). Several scenarios (~5 of 12) were relatively similar (that is, the points were close) to the Current Conditions scenario, as was the case for the hydrodynamic vectors described in the previous paragraph. There was only moderate change from the Current Conditions outcome associated with the without-development scenarios or with the Median Future and Median Future, −10 cm SLC scenarios. The extreme climate change (i.e., Dry Future) and the effect of rise in sea levels under a drier future climate were the least similar to the other scenarios.

Interpretations of the relative distances on the ordination plot (Fig. 4) can also be used to rank the relative effects of the different factors included across multiple scenarios. For example, the effect of water extraction (as included in the Current Conditions scenario) had a similar effect to an increasingly dry future climate in the absence of extraction (i.e., see the trend in Fig. 4 from Without Development, to Median Without Development and Dry Without Development scenarios). With extraction, however, there was only a small shift due to the Median Future scenario, but a much larger change was associated with the Dry Future scenario; note also that the direction of change shifted from up the ordination plot to across to the left. Small drops in sea level on top of those effects made little change for either future climate projection. In contrast, either a modest or large rise in sea level caused a large shift downward in the ordination space (Fig. 4) when combined with either future climate projection. In summary, we conclude that, by themselves, water extraction or trends in climate (as modeled here) have similar effect, but also interact strongly with each other to produce a contrasting outcome and again with SLC to produce yet different mixes of ecosystem states (as can be seen by some points falling in all four quadrants of the ordination space in Fig. 4).

Discussion

The ecological model used here was an empirical model where existing data for a region, the Coorong, had been statistically analyzed and modeled to identify relationships between the biota that occur within the system at any one point in time, and was explicit about the environmental conditions under which these biota occur (Lester and Fairweather 2011). Therefore, the assemblages are defined as “ecosystem states” and the drivers are the environmental variables associated with those states. The limitations of this model have been discussed in detail elsewhere (Lester and Fairweather 2011), but relevant limitations for this paper are summarized in Appendix B. The focus here was the
use of the model developed by Lester and Fairweather (2011) as a predictive tool for scenario analyses. Physical variables that were associated with ecological responses included water levels and salinities, so, in exploring a number of scenarios, water levels and salinities were modeled using a hydrodynamic model (Webster 2010). Ecological responses were then assessed by predicting the ecosystem states likely to occur under each of the simulated salinity and water level regimes. We were able to successfully represent a set of scenarios of interest to the managers of the region, providing a mechanism with which those managers could identify benefits and costs associated with a range of possible future scenarios for the region (Schlüter et al. 2006, Sutherland 2006). Many previous scenario modeling attempts in aquatic ecosystems have focused on the link between climate, water availability, and hydrology (e.g., Powell 2008), salinity (Lund et al. 2010), or sediment dynamics (e.g., Adler 2008), providing vital information regarding such specific aspects of possible future outcomes from different management strategies, but without modeling ecosystem responses explicitly. However, for specifically ecological objectives, such approaches do not address nonlinearities in ecological response to hydrology (Potts 2009, Zweig and Kitchens 2009), and scenario modeling approaches that explicitly include ecological response, such as that used here, may be necessary. Our approach, along with that used by Zweig and Kitchens (2009), is one that is capable of providing an explicit link between climate and management scenarios, hydrodynamics, and ecology and offers an alternative to other approaches such as modeling habitat suitability (e.g., Schlüter et al. 2006).

The approach of defining ecosystem states, as used here for scenario analysis, potentially has significant implications for the management of other estuaries, or other ecosystem types, such as floodplain wetlands. We were able to demonstrate the general utility of this approach of using scenario modeling in combination with a whole-of-system ecological model to elucidate the potential consequences of management decisions (as emphasized by Sutherland 2006), and, importantly, the relative impact of various interacting factors (e.g., climate-related changes in flow, SLC, and extraction levels). This scenario modeling exercise was particularly of use in highlighting unexpected impacts (e.g., interactions between climate, extractions, and SLC) and its use is not likely to be limited to estuaries like the Coorong. Such tools increase our understanding of dynamics of the system under study, in the manner identified by Schlüter and Pahl-Wostl (2007), allowing for the design of more effective management strategies and should be employed more broadly. The simplicity of the hydrodynamic and ecological response models gives rise to several advantages. First, the models are easily represented in the form of conceptual diagrams (e.g., see Lester and Fairweather 2011), avoiding perceived complexities in application and understanding that has previously been a barrier to adoption (Lester et al. 2011). Second, the form of the models appeals to stakeholders’ intuitive understanding of the links between environmental conditions and the biota of the system. Finally, the models can both be run in quite short time frames (e.g., within hours once the scenarios have been specified). Thus, this method represents a framework under which hundreds of scenarios can be run in manageable and practicable time frames. It is a powerful, yet simple tool where multiple plausible futures can be rapidly and objectively considered, enabling managers to identify likely outcomes of environmental watering strategies and justify the diversion of water from other possible uses (Schlüter et al. 2006, Poff et al. 2010).

The scenarios used here included modeled differences in water extraction, potential future climates, and SLC, so that substantial differences both in the hydrodynamics and the mix of ecosystem climates, and SLC, so that substantial differences both in the hydrodynamics and the mix of ecosystem states were simulated across the range of scenarios, suggesting that the models are sensitive enough to describe ecologically meaningful change in the region. Comparison of all scenarios against a baseline scenario that has been calibrated against measured data strengthened the notion that changes identified among scenarios are ecologically relevant. These calibrations revealed a high level of concordance for the hydrodynamic model (Webster 2010) and somewhat mixed results for the ecosystem states model, partly due to the limited availability of earlier data, but consistency in the trends observed and the timing of degradation (Lester and Fairweather 2009).

**Limitations of these scenario analyses**

There are limitations in this type of scenario assessment pertaining to the types of scenarios that can be modeled. For example, when considering SLC, it is only possible to address changes associated with the physical raising and lowering of sea level, not any associated changes in storminess that may accompany SLC (Gillanders et al. 2011), nor the potential for the sand dunes separating the Coorong from the Southern Ocean to be breached. In that particular example, separate modeling has shown that those dunes are unlikely to be breached in the next 50 years (Short and Cowell 2009), but there remain situations that will not be captured by scenario modeling of the type applied here. Similar caveats apply with respect to climate change.

Also, the model described here uses the number of days of no flow as a primary threshold between the healthier and less healthy ecosystem states. Thus, it is possible to imagine scenarios of additional small flows that would result in a veritable trickle of water that would meet the condition of flow, but potentially have very small ecological benefits. Thus, the model used here for scenario analyses should not be used for management scenarios that involve active changes to flows.
across the barrages and an alternative model based less explicitly on the presence or absence of barrage flows is needed in those cases (see Lester and Fairweather 2009).

Relative impact of climate change and extraction decisions

Our approach to this scenario modeling has allowed for independent appraisal of overall climatic shift and SLCs that are thought to be possible in the future. The future climates, as modeled, largely operate through changed rainfall and evaporation in the Murray-Darling Basin, and hence modify the amounts of water flowing over the barrages into the Coorong. The SLC modeled spanned the range of conditions predicted for the region (CSIRO Marine and Atmospheric Research 2008) from a modest fall (where sea-level rise is dwarfed by uplift of land) to modest or more pronounced rises. The inclusion of these factors separately or in combination into different modeled scenarios is a case where more than a single factor in future climate change has been examined, an all-too-rare inclusion in ecological studies (a similar plea for multifactorial experiments on climate change has recently been made by Russell et al. 2009 and Wernberg et al. 2012 because too many studies examine temperature effects alone).

Here, we were able to include climate change effects promulgated from evaporation, rainfall, flows, and SLC in just 12 scenarios because of a conscious effort to consider the range of potential effects that a changing climate may have. Our ability to elucidate the likely impact of climate change does, however, depend on the ability of the scenarios included herein to accurately represent the manner in which climate change develops. The timing of future flows is one of the least well-understood aspects of climate change (Aldous et al. 2011), and variability of flows is expected to increase. Groundwater dynamics are also likely to change (Aldous et al. 2011). More or less variability in barrage flows, in particular, would potentially result in very different impacts on Coorong hydrodynamics and ecological condition.

Based on this assessment, however, climate change, when combined with current extraction levels in the Basin, has the potential to be devastating to the ecosystem states of the Coorong. Previous studies have suggested that estuaries in southern Australia are likely to become warmer and drier (as reviewed by Aldous et al. 2011 and Gillanders et al. 2011), with changes to salinity and estuarine mouth morphology highlighted as critical. In our attempt to quantify some of those changes, the hydrodynamics of the Coorong predicted under median and, in particular, dry-climate projections were surprisingly bad. Hypersaline conditions developed as predicted (Gillanders et al. 2011), but the degree to which this occurred was surprising. For example, salinities in the South Lagoon under the Dry Future scenario are predicted to be in excess of 300 g/L (≥8 times seawater), and the number of consecutive days without flow may extend to ≥2500 (nearly 7 years). Salinities of this magnitude exceed the tolerances of almost all Coorong biota likely resulting in an extremely depauperate biotic assemblage. During a recent drought where salinity reached 200 g/L, no fish species remained in the South Lagoon, where only brine shrimp were able to thrive (Brookes et al. 2009, Gillanders et al. 2011). While this scenario did not allow for specific management actions within the region aimed to reduce the impact of extended dry periods (e.g., dredging of the Murray Mouth to allow more seawater into the Coorong), the simulated effects were startling, and it is unlikely that engineering solutions that have been considered in the past (e.g., dredging of the Murray Mouth) would be more effective at maintaining overall ecological condition of the region than they were during a recent drought (see Kingsford et al. 2011).

The long periods of drought conditions within the Median and Dry Future scenarios were predicted to cause extended periods dominated by degraded ecosystem states. Also of concern was the rapid switching between healthier and more degraded states. This increased instability of the ecosystem states within the system may increase the vulnerability of the Coorong to individual species loss and other major changes within the system. This risk would be due to the lack of time between droughts for biota to recover, with ecosystem recovery after drought known to require considerably more time than recovery after flooding (Lake 2000) and to likely increase with increasing length of drought.

SLC had an interesting effect on the hydrodynamic and ecological conditions of the Coorong. SLC altered the level of marine influence on the estuary (as suggested by Lund et al. 2010, Gillanders et al. 2011) but, for the most part, increases in sea level appeared to limit the effect of prolonged hydraulic disconnection between the North and South Lagoons. Hydrologic disconnection currently occurs between the two lagoons approximately seasonally, where local seasonal falls in sea level in late spring restrict the mixing that occurs between the North and South Lagoons, particularly in the absence of moderate to large barrage flows. As a result, evaporative losses from the South Lagoon cannot be replaced by flows from the North Lagoon and evapoconcentration occurs, resulting in low water levels and high salinities in late summer and early autumn (Webster 2010). The period of effective disconnection was longer in scenarios modeling possible future climates without SLC or with a fall in sea levels, but was shorter under SLC, thereby mitigating the worst effects seen in the earlier scenarios. This again illustrates the interaction between separate effects of climate change that led Russell et al. (2009) and Wernberg et al. (2012) to emphasize the utility of multifactorial experiments.

Investigating scenarios excluding current extraction levels and water resources infrastructure in the MDB enabled us to identify the relative contribution of climate change and SLC to the possible future ecology of the
Coorong, as opposed to that due solely due to water management. It is evident from those scenarios that, in the absence of water resource development, the impact of climate change would be relatively small, but in combination with that development, the impact is likely to be catastrophic as climate change exacerbates the impact of other stressors (Aldous et al. 2011). However, this provides a clear direction for the management of the region. Better management of water allocation upstream, through changes to the level and pattern of extraction, could lessen impacts from future droughts, and the volumes of additional fresh water via specified environmental flows (Aldous et al. 2011) from the River Murray needed to do so are within the realm of possibility (e.g., as opposed to returning to our without-development conditions; see Lester et al. 2011). This places the future ecological condition of the Coorong within the control of managers and decision-makers in the MDB.

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**SUPPLEMENTAL MATERIAL**

Appendix A

Map of the Coorong (Ecological Archives A023-051-A1).

Appendix B

Ecosystem response model (Ecological Archives A023-051-A2).

Appendix C

Development of a predictive model (Ecological Archives A023-051-A3).

Appendix D

Threshold analyses (Ecological Archives A023-051-A4).