A dynamic hydrological Monte Carlo simulation model to inform decision-making at Lake Toolibin, Western Australia

Stuart Jones, Peter Lacey, Terry Walshe*

School of Botany, The University of Melbourne, VIC 3010, Australia
Western Australia Department of Environment and Conservation, Hough Street, Narrogin, WA 6312, Australia

Article info
Article history:
Received 13 March 2008
Received in revised form 13 October 2008
Accepted 22 November 2008
Available online 29 December 2008

Keywords:
Monte Carlo simulation
Uncertainty
Water balance
Salt balance
Secondary salinity
Bird habitat
Lake Toolibin

Abstract
Lake Toolibin, an ephemeral lake in the agricultural zone of Western Australia, is under threat from secondary salinity due to land clearance throughout the catchment. The lake is extensively covered with native vegetation and is a Ramsar listed wetland, being one of the few remaining significant migratory bird habitats in the region. Currently, inflow with salinity greater than 1000 mg/L TDS is diverted from the lake in an effort to protect sensitive lakebed vegetation. However, this conservative threshold compromises the frequency and extent of lake inundation, which is essential for bird breeding. It is speculated that relaxing the threshold to 5000 mg/L may pose negligible additional risk to the condition of lakebed vegetation. To characterise the magnitude of improvement in the provision of bird breeding habitat that might be generated by relaxing the threshold, a dynamic water and salt balance model of the lake was developed and implemented using Monte Carlo simulation. Results from best estimate model inputs indicate that relaxation of the threshold increases the likelihood of satisfying habitat requirements by a factor of 9.7. A second-order Monte Carlo analysis incorporating incertitude generated plausible bounds of [2.6, 37.5] around the best estimate for the relative likelihood of satisfying habitat requirements. Parameter-specific sensitivity analyses suggest the availability of habitat is most sensitive to pan evaporation, lower than expected inflow volume, and higher than expected inflow salt concentration. The characterisation of uncertainty associated with environmental variation and incertitude allows managers to make informed risk-weighted decisions.

© 2008 Elsevier Ltd. All rights reserved.

1. Introduction

Risks and uncertainties are increasingly recognised as important elements of decision-making (Burgman, 2005). Deterministic models that ignore uncertainty implicitly oblige decision-makers to be risk-neutral. Here we present a case study of environmental decision-making informed by stochastic simulation that explicitly documents uncertainty and hence accommodates an attitude of risk-aversion (or an appetite for risk) among decision-makers. The case study involves hydrological dynamics of a lake system in southwestern Australia. Krzysztosowicz (2001) outlines the deficiencies of deterministic mass-balance models prevalent in hydrological forecasting and advocates probabilistic approaches from common sense and decision-theoretic perspectives. The site-specific case study presented here provides illustration of transportable methods for characterising uncertainty and their relevance to environmental decision-making.

Much of the native vegetation of the 300–600 mm rainfall zone of southwestern Australia has been cleared for agriculture over the past 150 years (George et al., 1995). Consequently, deep-rooted perennials have been widely replaced with shallow-rooted annual crops. This has significantly changed catchment-wide water balances across the region, with reduced transpiration leading to increased upper-catchment recharge and rising lower-catchment watertables (Cramer and Hobbs, 2002; Peck, 1978). Rising watertables have mobilised soil-stored salt to the surface. The resulting salinisation is known as 'dryland' or secondary salinity, a major threat to agricultural production and conservation values, both in Australia and worldwide (Williams, 1999). The agricultural zone of southwestern Australia supports some of the most diverse biota in Australia, of which approximately 450 plant and 400 animal species are now considered threatened, largely as a result of secondary salinity (McNamara, 2004).

Lake Toolibin is fed predominately by the intermittent flows of the Northern Arthur River, which drains a catchment area of over 49 000 ha (Fig. 1). The region has a Mediterranean climate, with 70% of the approximate average annual rainfall of 400 mm falling...
between May and September. The average maximum temperature is 31 °C in the hottest month, January. Pan evaporation averages 4.5 mm/day over the year, varying from 1.5 mm/day in June to 8.7 mm/day in January. Mean annual flow for the Northern Arthur River for the period 1979–2000 was 272 ML (10th percentile = 0.03 ML, 90th percentile = 2490 ML). Median streamflow salinity over the same period was 2110 mg/L TDS (10th percentile = 400 mg/L TDS, 90th percentile = 4200 mg/L TDS). The catchment has been extensively cleared, with up to 97% of native vegetation removed. Watertables beneath the lake and immediate valley floor upstream have been stable since the mid 1990s. However, watertables in the upper catchment continue to rise between 0.1 and 0.3 m/yr. Dryland salinity currently affects 8% of the catchment, but steady state modelling suggests up to 24% is at risk (Dogramaci et al., 2003; George et al., 2005).

The historically fresh to brackish Lake Toolibin is a Wetland of International Importance under the Ramsar Convention. When inundated, it is the richest breeding habitat for waterbirds in southwest Australia, with 25 of the 49 species observed at the lake breeding on at least one occasion (Froend et al., 1997; Halse, 1987). It is also the last remaining wetland with substantial mixed stands of the woodland tree species *Casuarina obesa* and *Melaleuca strobophylla*, a once–common association prior to secondary salinisation (Froend et al., 1997; Halse et al., 1993a).

In the 1980s it was recognised that the vegetation of Lake Toolibin was declining because of waterlogging and salinisation. The watertable had risen to within 1–2 m of the lakebed, leading to increased salinity and a decline in oxygen availability in the root zone. The physiological stress caused by groundwater salinity was compounded by an apparent increase in the salt load of surface water inflows and subsequent concentration via evaporation. These stressors resulted in the death of all mature *Eucalyptus rudis* trees over the entire lakebed, and patchy decline in the more tolerant *C. obesa* and *M. strobophylla* (Froend et al., 1987).

Research into the lake’s hydrology and ecology formed the basis for a recovery plan, including identification of specific engineering interventions (Froend et al., 1997; Wallace et al., 1994). In 1995, a separator gate and channel were constructed to divert saline flows from the Northern Arthur River around the lake for disposal to the degraded Lake Taarblin to the south. Construction of the channel also created a barrier between Lake Toolibin and the occasional flows of the North West Creek. Groundwater pumps were installed on the lakebed in 1997 to reduce waterlogging and capillary rise of salt associated with the shallow watertable below the lake (Figs. 1 and 2). Together with below average rainfall in recent years, these initiatives have arrested the trend in vegetation decline (George et al., 2005). However, there has been no significant inflow for the provision of bird habitat since 1996.

One option for promoting habitat is to relax the salinity threshold at which water is diverted around the lake. Currently, the operational threshold above which inflows are diverted is 1000 mg/L TDS. Ex-situ studies examining the toxicology and physiology of lakebed vegetation suggest this threshold may be conservative (Carter et al., 2005; Froend et al., 1987). To allow inflows of higher salt concentration, an effective outlet is required to drain the lake during periods when evaporation dominates inflow, thereby avoiding intolerable concentration of salt in the lake and deposition of salt on the lakebed. The current lake outlet sits 0.2 m above the lakebed. It is proposed that the outlet be lowered and a drain constructed to link the outlet with the lowest areas of the lake floor, in order to more effectively drain the entire lake. The model we develop here assumes implementation of this proposal.

Relaxing the threshold at which water is diverted is not without risk. Observations made at other wetlands in the region suggest that the richness of waterbird species visiting or breeding is approximately halved when the water salinity rises and the dominant tree species die (Halse et al., 1993b). Of the two dominant species on the lakebed, *M. strobophylla* is substantially more...
vulnerable to hydrological impacts than *C. obesa* (Carter et al., 2005; Froend et al., 1987).

The pathways by which decline in *M. strobophylla* might be observed are shown in Fig. 3. The fault tree states that decline may be caused by extensive periods of inundation or drought stress. As a best estimate based on expert opinion (Ayyub, 2001), *M. strobophylla* is thought to be tolerant to continuous inundation for up to four years. The factors associated with drought stress are disaggregated in some detail. Drought stress due to excessive salt in the root zone can result from salt stored in surface soils at concentrations greater than 160 mS/m or a groundwater depth less than 2 m below the surface. The current concentration of salt in the root zone is uncertain. However, if groundwater pumps continue to operate, it is assumed that any surface water in the lake less than 5000 mg/L TDS will move vertically through the soil profile and leach soil stored salts. Drought stress due to insufficient surface water will result if annual rainfall is less than 350 mm and there are no surface water inflows from the Northern Arthur River. Saline inflow from groundwater at less than 1 m depth below the surface will be a threat only if groundwater pumps are not operating. As a best estimate, the critical threshold for surface inflows from the Northern Arthur River is 5000 mg/L TDS.

A concentration of 5000 mg/L represents a subjective risk-neutral best estimate of vegetation tolerance and may in fact expose the lakebed vegetation to hydrological stress. In the long run, any decline in vegetation condition will compromise the quality of bird habitat. The possibility of adverse outcomes needs to be weighed against the degree of improvement in waterbird habitat. The focus of the work presented here is characterisation of the expected improvement in successful provision of breeding habitat associated with relaxation of the inflow salinity diversion threshold from 1000 to 5000 mg/L, and the uncertainty surrounding that expectation. We describe the development and results of a dynamic Monte Carlo simulation model for the water and salt balance of Lake Toolibin, including second-order analysis to account for incertitude.

2. Methods

Monte Carlo simulation uses statistical distributions to represent different kinds of uncertainty, combining them to generate estimates of the likelihood of specified outcomes. It is an effective method for characterising risks and uncertainty in circumstances where considerable data describing system dynamics are available (Vose, 2000). Examples of its use in environmental management include exploration of the interactive impacts of land use and climate change on runoff characteristics (Samaniego and Bardinossy, 2006). Wu and Tsang (2004) examined flux in the availability of spawning habitat and its implications for the viability of salmonid populations. Moschandreas and Karuchit (2002) used Monte Carlo simulation to quantify health risks associated with exposure to pesticides.

Other methods may be used where data are sparse or where expert opinion is the dominant source of information. Imprecise probabilities associated with expert judgement may be treated using Depmster–Shafer reasoning (Caselton and Luo, 1992). Hobbs (1997) and Pollino et al. (2007) regard Bayesian methods as an intuitive and theoretically sound basis for combining expert opinion and data. Fuzzy-set theory may be useful where uncertainty is language-based (Zadeh, 1983). The availability of substantial long-term monitoring records at Lake Toolibin suggested Monte Carlo simulation was the most appropriate method for the case study described here.

2.1. First-order Monte Carlo analysis

To assess the merit of relaxing the diversion threshold, an ecological endpoint representing successful provision of breeding habitat for waterbirds is required. The core hydrological elements
of habitat involve the depth and period of inundation. Halse (1987) categorises the feeding habits of waterbirds observed at Lake Toolibin into eight guilds, of which the most hydrologically constrained are the divers. Collated field observations suggest that water depth has little effect on the abundance of diving birds when the lake depth is at 1 m or more but that numbers decline rapidly, and most species are absent, when the depth is less than 1 m. Breeding activity occurs mainly in spring, although some species such as the Grey Teal and Pink-eared Duck may breed at any time of year. Here we define the ecological endpoint for success in the provision of habitat as continuous lake inundation at a depth greater than or equal to 1 m for six months or more. Success is additionally constrained by the requirement to maintain the lake at a salinity concentration less than the critical threshold (1000 or 5000 mg/L) throughout the period of inundation.

A dynamic Monte Carlo simulation model was developed to model the lake system against the ecological endpoint, whilst enabling description of uncertainty arising from environmental variation. The model is based on a water and salt mass balance. The balance of mass present at any one-time step is simply the mass balance of the previous time step, plus the net sum of the fluxes during the current time step.

The water balance of the lake was described as

$$V_{t+1} = V_t + IF_v + RF_v - (L_v + ET_v + OF_v),$$

(1)

where $V_{t+1}$ is volume at time $t+1$, $V_t$ is volume at time $t$, $IF_v$ is surface inflow in a single time step, $RF_v$ is direct rainfall input in a single time step, $L_v$ is leakage of water through the lakebed in a single time step, $ET_v$ is evapotranspiration in a single time step, and $OF_v$ is outflow volume in a single time step.

The salt balance was described as

$$S'_{t+1} = S_t + IF_s + RF_s + L_s - OF_s,$$

(2)

where $S'_{t+1}$ is salt concentration at time $t+1$, $S_t$ is salt load at time $t$, $IF_s$ is surface inflow salt load in a single time step, $RF_s$ is rainfall salt load in a single time step, $L_s$ is net salt load change from leakage through the lakebed in a single time step, and $OF_s$ is outflow salt load in a single time step. The time step used in both equations was one month.

Stochasticity is incorporated in the mass balance models by specifying statistical distributions to represent variability in the drivers of lake volume and salinity, which are then sampled over repeated iterations to generate a distribution of outcomes. Where sufficient data are available, distributions can be fitted by eye or with goodness-of-fit tests. A combination of the two was used to fit the distributions for this study, whereby a subset of candidate distribution shapes were selected by visual inspection, and then the final distribution selected according to the highest value obtained for the goodness-of-fit test statistic calculated for all candidates in the subset. We used the Anderson–Darling test (Anderson and Darling, 1954) to examine goodness-of-fit because it is more sensitive to departures in the tails of fitted distributions than the commonly used Kolmogorov–Smirnov test. Fitted distributions were truncated to avoid simulations sampling from implausible extremes of tails.

The specification of distributions fitted in the model is summarised for key variables in Table 1. The gauging station situated at Toolibin Lake begins to overflow (OF) when the lake depth is approximately 1.75 m. To estimate the rate of outflow, we calibrated the water balance model against historical records. The best calibration was achieved with an outflow rate of 0.4 × 10^6 m^3/ month.

Toolibin Lake starts to overflow (OF) at a volume of 2.7 × 10^6 m^3 (Stokes and Sheridan, 1985), equating to a depth of approximately 1.75 m. To estimate the rate of outflow, we calibrated the water balance model against historical records. The best calibration was achieved with an outflow rate of 0.4 × 10^6 m^3/ month.

We fitted a single lognormal distribution to salinity concentration data captured at the Northern Arthur River gauging station for all observations where flow was greater than zero (IF). An inverse relationship between inflow volume and salt concentration for Toolibin Lake has been reported in previous work (Dogramaci et al., 2003; George et al., 2005). Using monthly salinity and flow records from the gauging station we sought to specify the strength of the association for Monte Carlo simulation through calculation of Spearman’s rank correlation coefficient. We found the correlation did not vary significantly seasonally ($\rho = 0.10$, two-tailed). We therefore used a fixed value of $-0.283$ calculated from the pooled data to specify the dependency between flow volume and salt concentration.

The salt concentration of rainfall ($RF_s$) was represented as a normal distribution with a mean of 7.2 mg/L (Hingston and Galitis, 1976) and standard deviation of 1.0 mg/L. Salt loss from leakage ($L_s$) through the lakebed and outflow ($OF_s$) are dynamic, depending on the sum of fluxes in the previous time step. We assumed perfect mixing in the lake for salt loss through leakage and outflow.
incertitude. The family of output distributions represents mental variation. The family of output distributions represents any single realisation reflects environmental variation and are fixed. In second-order analysis, the Monte Carlo, stochastic parameters are estimated to reflect environmental variation. We conducted two forms of sensitivity analysis: second-order Monte Carlo and parameter-specific sensitivity analysis. Second-order Monte Carlo seeks to separate uncertainty associated with natural variation from that of incertitude. Incertitude refers to a lack of knowledge about models or parameters. It can be reduced by collecting more and better data. Variability can be better understood and more reliably estimated, but cannot be reduced by collection of additional data (Hattis and Burmaster, 1994; Vose, 2000).

Second-order Monte Carlo provides a way of treating and communicating these two sources of uncertainty separately. Insights from results allow model users to identify steps that can be taken to reduce total uncertainty, to gauge the implications of system changes, and to avoid serious errors stemming from the confounding of variability and incertitude (Frey and Rhodes, 1996; Hession et al., 1996; Hoffman and Hammonds, 1994; Moschandreas and Karutch, 2002; Wu and Tsang, 2004). In standard first-order Monte Carlo, stochastic parameters are estimated to reflect environmental variation and are fixed. In second-order analysis, the parameters are themselves drawn from statistical distributions that reflect incertitude about true values. Second-order Monte Carlo involves a nested procedure consisting of multiple realisations of model parameters and correlation structures. Each realisation is iterated as in standard Monte Carlo simulation, resulting in a family of output distributions. Any single realisation reflects environmental variation. The family of output distributions represents incertitude.

First-order analysis ignores sampling error in data used to fit distributions and derive correlation structures. Fitting a single distribution to historical data assumes stationarity. Temporal trends violating this assumption may include changing rainfall patterns associated with climate change or increased salt loads associated with an incrementally rising watertable. The second-order analysis we conducted is summarised in Fig. 4. Due to computational overheads, we restricted analyses to initiating conditions involving only the 90th percentile of winter flows, for operating thresholds for the diversion of surface flows of both 1000 and 5000 mg/L TDS. The treatment of incertitude in correlation structure involved calculation of 90% confidence intervals for the Spearman’s rank correlation coefficients between inflow volume and rainfall volume over 2005–2006 and inflow volume and inflow salinity [0.427, 0.125] using the method described by Altman and Gardner (2000). Using trial simulations, we established best case and worst case correlation structures using the output cumulative distribution of successful provision of bird breeding habitat at six months as a benchmark. For each operating threshold, second-order simulations were conducted for i = 3 correlation structures involving best estimate (first-order), worst case and best case. Within any single correlation structure, we sampled k = 100 realisations from uniform distributions describing plausible bounds for the mean of all fitted distributions to account for parameter incertitude. Using subjective judgement, we considered plausible bounds for all distributions to be +/– 20% of the best estimate (first-order) fit for the mean. Within any single parameter realisation, s = 1000 iterations were performed. Second-order Monte Carlo affords little insight into which variables or parameters are of greatest importance in their influence on model output because any single realisation of the model involves random departure from first-order point estimates for all variables simultaneously. The sensitivity of model output to error in a specific parameter, sp, can be quantified using the expression,

$$s_p = \frac{\Delta V/V}{\Delta P/P}$$

where ∆V is the magnitude of change in the output variable V relative to the base case, and ∆P is the manipulated change in the parameter of interest P relative to the base case (Beck, 1983). We conducted parameter-specific sensitivity analyses for input describing inflow volume, inflow salinity, pan evaporation and rainfall for initiating conditions involving the 90th percentile of winter flow and an operating threshold of 5000 mg/L. We changed the central tendency of first-order fitted distributions by +/– 20% one variable at a time and re-ran the simulation, with each simulation comprising 10 000 iterations.

### 3. Results

First-order simulation results for scenarios initiating in January, April and October all reported zero probability of providing bird

### Table 1

Summary of key variables for which statistical distributions were specified to characterise environmental variation in water and salt dynamics in Toolibin Lake. Notation for variables refers to terms used in Equations (1) and (2).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Temporal resolution</th>
<th>Fitted distribution</th>
<th>Correlations</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflow volume, (IF_v)</td>
<td>m³</td>
<td>Seasonal</td>
<td>Lognormal</td>
<td>Rainfall, (IF_v) (+)</td>
<td>Northern Arthur River flow records 1979–2005</td>
</tr>
<tr>
<td>Rainfall, (RF_r)</td>
<td>mm</td>
<td>Monthly</td>
<td>Gamma</td>
<td>Inflow volume, (IF_v) (+)</td>
<td>Northern Arthur River rainfall records 1979–2005</td>
</tr>
<tr>
<td>Inflow salinity, (IF_s)</td>
<td>mg/L</td>
<td>Fixed</td>
<td>Lognormal</td>
<td>Inflow volume, (IF_v) (+)</td>
<td>Northern Arthur River salinity records 1979–2005</td>
</tr>
<tr>
<td>Rainfall salinity, (RF_s)</td>
<td>mg/L</td>
<td>Fixed</td>
<td>Normal</td>
<td>None</td>
<td>Adapted from Higgott and Galilitis (1976)</td>
</tr>
<tr>
<td>Vertical hydraulic conductivity(a)</td>
<td>m/s</td>
<td>Fixed</td>
<td>Normal</td>
<td>None</td>
<td>Adapted from Dogramaci et al. (2003)</td>
</tr>
<tr>
<td>Groundwater level(b)</td>
<td>mAH</td>
<td>Monthly</td>
<td>Logistic</td>
<td>None</td>
<td>Dogramaci et al. (2003)</td>
</tr>
<tr>
<td>Pan evaporation(ab)</td>
<td>mm</td>
<td>Monthly</td>
<td>Normal</td>
<td>None</td>
<td>Narrogin meteorological station records 1965–1985</td>
</tr>
<tr>
<td>Pan evaporation factor(ab)</td>
<td>Unitless</td>
<td>Monthly</td>
<td>Normal</td>
<td>None</td>
<td>Adapted from Dogramaci et al. (2003)</td>
</tr>
</tbody>
</table>

- \(a\) Components of lakebed leakage, \(L_c\)
- \(b\) Components of evapotranspiration, \(ET_v\)
habitat for 1 month or more, irrespective of whether the operating threshold for inflows was set at 1000 or 5000 mg/L TDS.

The results for winter (90th percentile of July flow as the initiating event) were more informative. Model outputs for the two operating thresholds are shown graphically in Fig. 5. There is a clear qualitative difference between the two thresholds. The probability of one month or more of water of >1 m depth in the lake is \( \approx 0.2 \) for a threshold of 1000 mg/L and \( \approx 0.8 \) for a threshold of 5000 mg/L. No iteration in either scenario extended to 48 months. The maximum iteration lengths were 20 and 41 months for the 1000 and 5000 mg/L thresholds, respectively.

Seasonal influences are clearly illustrated in Fig. 5. The timing of failure (falling below 1 m depth or rising above the specified salinity threshold) is concentrated around summer months, some six months after the initiating event in July. Fig. 5a suggests that with an operating threshold of 1000 mg/L there is negligible chance of continuous habitat provision beyond the first summer. The additional mode around 16 months in Fig. 5b suggests some chance of habitat being provided continuously up to the second summer after the initiating flow event where an operating threshold of 5000 mg/L is employed.

Results of second-order analyses are presented as cumulative distributions (Fig. 6). Cumulative distributions show the probability of failing to meet specified bird habitat requirements for \( m \) months or less. Seasonal effects are reflected in the changing gradient of the curves. That is, the steeper gradients around three to nine months reflect clustering in the timing of failure around the warmer, drier summer months. Fig. 6a includes 18 distributions, comprising the two operating thresholds (1000 and 5000 mg/L), three correlation structures (best estimate, best case and worst case) and three parameter realisation percentiles (5th, 50th and 95th percentiles). Fig. 6b summarises the curves corresponding to each operating threshold. The 50th percentile and best estimate correlation structure is equivalent to the first-order analysis (Fig. 5). The curves in Fig. 6a are clustered according to operating threshold and realisation percentile. That is, the difference between best case and worst case correlation structures is small.

The complement of a cumulative curve is the probability of success (i.e., \( 1 - \) the probability of failure). For the benchmark of six months that we used to define successful provision of bird breeding habitat, the probability of success under the operational thresholds of 1000 and 5000 mg/L for first-order analyses is 0.052 and 0.506,
respectively. That is, for the initiating conditions specified, there is an approximate ten-fold increase in the chance of six consecutive months or more of inundation greater than 1 m depth and less than the operating threshold for salt concentration. Plausible bounds on incertitude (Fig. 6b), report an interval of [0.017, 0.134] for the probability of success under the 1000 mg/L threshold and [0.351, 0.637] for the 5000 mg/L threshold. These results provide an interval for the magnitude of the improvement factor of [2.6, 37.5] (Table 2).

Fig. 7 shows output cumulative distributions for parameter-specific sensitivity analyses. For all variables examined, the reference case refers to an initiating event of 90th percentile flow in July and an operating threshold of 5000 mg/L. The complexity of hydrological interactions captured in the model results in asymmetry around the reference case and variation in the magnitude of sensitivity over time.

Results of formal calculation of sensitivity at six months are shown in Table 3. At six months the model output is most sensitive to a decrease in inflow volume. Increases in inflow volume have little effect on the output, suggesting the failure condition associated with salinity dominates over the failure condition of falling below 1 m depth. Inflow salinity has a moderate and approximately symmetrical influence on output at six months. The model output is substantially sensitive to pan evaporation at six months, but is especially sensitive to lesser pan evaporation thereafter. The failure rate for the scenario involving a 20% decrease in pan evaporation is notably lower (i.e., the gradient of the curve is flatter) than the reference case and the 20% increase in the first summer (Fig. 7c), suggesting overestimation of pan evaporation in the model will tend towards erroneously pessimistic projections. Changes in rainfall have very little effect (Fig. 7d), although it is important to note that the sensitivity analysis refers only to direct input of water and salt into the lake through rainfall and not the indirect effects of inflow from the Northern Arthur River, which are explored separately (Fig. 7a and b).

4. Discussion

Results indicate a clear improvement in the likelihood of successful provision of bird habitat with relaxation of the operating threshold at which water is diverted around Toolibin Lake. The absence of overlap in curves accounting for incertitude between the 1000 and 5000 mg/L thresholds (Fig. 6) provides a significant argument for changing the threshold to 5000 mg/L. The magnitude of improvement is uncertain and needs to be weighed against possible risks to the condition of lakebed vegetation. Our analysis is best interpreted in a relative rather than an absolute sense. The probabilities of success for the two operating thresholds reported in Table 2 refer only to initiating conditions involving a large winter flow event. They cannot be extrapolated to other initiating conditions or interpreted as the per annum probability of successful habitat provision. The relative magnitude of improvement is a more robust measure of the effect of relaxing the operating threshold. A best estimate of an approximate ten-fold increase in the likelihood of suitable bird habitat conditions (with a plausible range of 2.6–37.5; Table 2) is the most succinct and appropriate summation of the decision-support outcome of this study.

We qualify these results with recognition that second-order Monte Carlo cannot guarantee inclusion of the true state of the system (Ferson, 1996). There are many possible choices for distribution shapes, parameters and correlation structures. Computational overheads prohibit exhaustive treatment of uncertainty. Limited data from the Northern Arthur River gauging station and nearby meteorological stations mean that for any variable in the mass balance model there are multiple distributions that fit the historical data (1979–2005; Table 1) for inflow salinity and rainfall (and indirectly, inflow) is especially dubious. George et al. (2005) informally infer an increase in mean inflow salinity from 1000 to 2000 mg/L throughout the 1990s. These authors report that monitored wertables beneath the lake and the immediate

| Table 2 |
The magnitude of improvement in the probability of successful provision of bird habitat through relaxing the operating threshold for diversion of inflows from 1000 mg/L to 5000 mg/L TDS. Bounds on probabilities reflect incertitude at six months. The lower bound for the improvement factor is the ratio of the lower bound for probability of success for 5000 mg/L and the upper bound for 1000 mg/L. The improvement factor upper bound is the ratio of the upper bound probability for 5000 mg/L and the lower bound probability for 1000 mg/L.

<table>
<thead>
<tr>
<th></th>
<th>Best estimate</th>
<th>Lower bound</th>
<th>Upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating threshold</td>
<td>1000 mg/L</td>
<td>0.052</td>
<td>0.017</td>
</tr>
<tr>
<td>Operating threshold</td>
<td>5000 mg/L</td>
<td>0.506</td>
<td>0.351</td>
</tr>
<tr>
<td>Improvement factor</td>
<td></td>
<td>9.7</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Fig. 6. Results of second-order Monte Carlo simulations for an initiating event equivalent to the 90th percentile of July flow and for the two operational thresholds (1000 mg/L and 5000 mg/L TDS) at which water can be diverted around (and released from) Toolibin Lake. (a) Family of curves comprising best estimate, worst case and best case correlation structures, and 5th, 50th and 95th percentiles for each month from k – 100 parameter realisations, (b) Summary of incertitude around first-order results (continuous lines) for an operating threshold of 1000 mg/L (dark grey) and 5000 mg/L TDS (light grey). Shading envelopes minima and maxima of all curves shown in (a).
upstream valley floor show that groundwater levels have been stable since the mid-1990s, while monitoring in the upper catchment shows rising watertables. We tested for the presence of temporal trends in rainfall and inflow salinity and found the results (not shown) were statistically non-significant. However, the power of the tests was generally low and non-significant results need not imply absence of a trend (Fairweather, 1991).

Even if non-stationarity has been insignificant in the past, climate change and the catchment’s progression to hydrological equilibrium will limit the reliability of future predictions based on historical records. Suppiah and Durack (2005) report plausible bound projections for future climate change in southwestern Australia. For the year 2030, predicted changes in seasonal rainfall vary from an approximate 15% decrease to a 5% increase. Mean annual temperatures are expected to increase by up to 2 °C. Under current land use and in the absence of management intervention, hydrological equilibrium is predicted to occur around 2100 (George et al., 2005). Our treatment of incertitude through second-order Monte Carlo analysis mitigates against overconfidence in the reliability of historical data to some extent, but collectively these factors mean that the predictive value of the modelling results can only be considered reasonable for conditions encountered in the next decade or so.

Longer-term predictions demand ongoing monitoring, model calibration and validation. Parameter-specific sensitivity analyses provide additional emphasis on inflow salinity, rainfall and pan evaporation as priorities for ongoing data capture. Poor specification of the distributions associated with these variables implies poor model predictions. Conversely, greater effort in monitoring and research aimed at better specifying these variables will provide greater precision and confidence in model output.

Monitoring and model updating also provides a means of cross-examining alternative perspectives on the mechanisms leading to salinisation. Dogramaci et al. (2003) and George et al. (2005) contend that saline groundwater intrusion into the surface flow has been the dominant cause of inflow salinisation in the past, and will remain a dominant factor into the future. In contrast, Cattlin et al. (2004) suggest the major driver of surface water salinisation is pondage on highly saline grey-clays occurring in the lower catchment and subsequent mobilisation of the salts. The modelling presented here can be extended to describe alternative drivers of hydrological change. When confronted with targeted monitoring data, the merit of alternative perspectives and associated management interventions can be assessed and models updated in an adaptive management framework (Walters and Holling, 1990).

Table 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Probability of success</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflow volume</td>
<td>0.509</td>
<td>0.07</td>
</tr>
<tr>
<td>+20%</td>
<td>0.509</td>
<td>0.07</td>
</tr>
<tr>
<td>−20%</td>
<td>0.176</td>
<td>3.25</td>
</tr>
<tr>
<td>Inflow salinity</td>
<td>0.380</td>
<td>1.22</td>
</tr>
<tr>
<td>+20%</td>
<td>0.380</td>
<td>1.22</td>
</tr>
<tr>
<td>−20%</td>
<td>0.599</td>
<td>0.96</td>
</tr>
<tr>
<td>Pan evaporation</td>
<td>0.220</td>
<td>2.81</td>
</tr>
<tr>
<td>+20%</td>
<td>0.220</td>
<td>2.81</td>
</tr>
<tr>
<td>−20%</td>
<td>0.623</td>
<td>1.27</td>
</tr>
<tr>
<td>Rainfall</td>
<td>0.531</td>
<td>0.31</td>
</tr>
<tr>
<td>+20%</td>
<td>0.531</td>
<td>0.31</td>
</tr>
<tr>
<td>−20%</td>
<td>0.493</td>
<td>0.09</td>
</tr>
</tbody>
</table>

5. Conclusion

The modelling presented here provides a synthesis of hydrological understanding of Toolibin Lake and a coarse approximation of the relative improvement in bird habitat expected in the short-term. Despite limitations this study suggests relaxation of the threshold at which water is allowed in to Toolibin Lake to
5000 mg/L TDS will provide substantially enhanced prospects for bird habitat. The fuller characterisation of uncertainty through second-order Monte Carlo analysis allows managers to make an informed decision on whether to proceed with relaxation of the threshold. The explicit inclusion of incertitude in second-order analyses provides a basis for decision-making that accommodates aversion or appetite for risk (Burgman, 1995; Finkel, 1994). Future calibration and validation of model structure and inputs will provide a sound basis for longer term predictions and a means of clarifying causal mechanisms of salinisation.

Acknowledgments

We thank Stuart Halse, Ken Wallace and Ryan Vogwill for assistance in formulating the problem addressed in this paper. Ray Froend and Richard George generously provided their address and expert opinion on the hydrological sensitivity of Melaleuca strobophylla and the hydrological dynamics of Lake Toolibin. The content of the paper was considerably improved after responding to comments received from three anonymous reviewers.

References


