Supplementary Material

The five-step Adaptation Tipping Points (ATP) methodology includes: (i) the determination of climate change effects on the system; followed by (ii) identifying key objectives and thresholds; (iii) the determination when standards were compromised in the past; (iv) analyzing when standards will be compromised in the future; and (v) to repeat step 1–4 for alternative strategies. The methodology depends on a close interaction with stakeholders to determine the aims of ecosystem management and to discuss adaptation measures. Below is a list of tables 1-7 with information on how we conducted this stakeholder engagement and how we applied the information in our case study area (Forrestdale Lake, Western Australia).

**Supplementary Table 1.** Participants of stakeholder workshops and interviews.

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| **Abbreviation** | **Actor** | **Role** |
| FOF | Friends of Forrestdale | Community conservation group: responsible for ecological monitoring, revegetation and rehabilitation works |
| COA | City Council of Armadale | Council: land allocation, drainage, groundwater use for irrigation |
| DOW | Department of Water | Water regulator: groundwater allocation and surface water monitoring of the wetland |
| DPAW | Department of Parks and Wildlife | Conservation authority: protecting biodiversity, visitor access, and coordinating local wetland management |
| WC | Water Corporation  | Water utility: responsible for groundwater abstraction and main drains around the wetland  |
| URB | Urbaqua | Groundwater research institute and non-for-profit consultancy |

**Supplementary Table 2.** The structure of the literature review and the interviews with stakeholders to design a conceptual eco-hydrological model for the wetland.

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| **Information for the conceptual eco-hydrological model** |
| *Literature review* |
| 1. How have the boundary conditions of the ecosystem changed over the last 25 years?
2. What are the (un)confined aquifers and geological layers?
3. How much groundwater is abstracted and where are the bores located?
4. What direction is the groundwater flow
5. What are the seasonal changes of surface- and groundwater in the wetland?
6. Which are the main common species groups compared to the socio-ecological objectives from the wetland management plan?
7. What are the effects of seasonal change of surface and groundwater on the different species groups?
8. What are the distinct wetland zones based on their connectivity with groundwater and dependence on surface water?

*Interviews* |
| 1. What is the timing of migratory birds to visit the wetland over the last 20 years?
2. What is the timing of leaving of migratory birds over the last 20 years?
3. What is the trend of total number of waterbirds and migratory birds?
4. What is the trend of species composition of birds, aquatic macro-invertebrates, foxes, and rare flora?
5. How often do bush fires occur and where do they occur in the wetland buffer zone?
6. How has the extent of invasive weeds covering the intermediate zone of the wetland changed over time?

*Hydrological model* |
| 1. What is the groundwater gradient in the superficial aquifer?
2. How are the groundwater table fluxes in autumn/winter and spring/summer?
 |
| 1. When are surface water and groundwater connected?
2. What is the groundwater gradient near the abstraction wells?
 |

**Supplementary Table 3.** Stakeholder discussion’s structure to determine alternative strategies.

|  |  |
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| **Topics discussed** | **Aim** |
| 1. Determine problem statement, objectives, drivers, and performance metrics of the wetland
 | 1. Eight critical socio-ecological objectives that depend on sufficient water levels
 |
| 1. Identify measures to maintain sufficient water levels
 | 1. Adaptation measures that were proposed formed the basis for further discussions on adaptive management
 |
| 1. Discuss the measures and the role of each actor
 | 1. Role of each actor as determined in policy and law
 |
| 1. Set priorities for each socio-ecological objective
 | 1. Initially all objectives are equal without prioritisation
 |
| 1. Determine the common objectives for wetland management and the adaptation measures proposed
 | 1. Reach consensus on a common problem
 |
| 1. Identify the priorities that actors have in local wetland management
 | 1. Discussion among actors for preferred adaptation measures
 |
| 1. Determine ecosystem processes and hydrological changes of the wetland
 | 1. Record historical and recent observation by experts from government departments to inform conceptual ecosystem models
 |
| 1. Determine preferred adaptation measures informed by conceptual ecosystem models and future water level estimations
 | 1. Reveal decision-making process of actors and the changes to adaptive ecosystem management
 |
| 1. Analyse ecosystem uncertainties perceived by stakeholders prior and after informed by conceptual ecosystem models and future water levels
 | 1. Use information to conceptualise the feedbacks (of stakeholders) within the socio-ecological system
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**Supplementary Table 4.** Critical socio-ecological objectives of the wetland.

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| **Socio-ecological objective** |
| 1. protect vegetation and mammals; fire and drought prevention |
| 2. prevent mosquitoes |
| 3. protect waterbirds |
| 4. protect frogs |
| 5. protect tortoises |
| 6. protect macro-invertebrates |
| 7. prevent exposure of Acid Sulphate Soils |
| 8. maintain sediment processes |

**Supplementary Table 5.** Proposed adaptation measures for groundwater and land-use management.

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| **Adaptation measure** |
| 1. Recoup unused entitlements (especially in groundwater capture zone of wetland).
 |
| 1. Restrict exempt use (especially in groundwater capture zone of wetland).
 |
| 1. Improve metering of licenses around the lake.
 |
| 1. Recover licenses through land-use change.
 |
| 1. Reduce Leederville aquifer abstraction.
 |
| 1. Implementing WSUD to redirect stormwater to lake from new developments around the lake.
 |
| 1. Sewer system to replace septic tanks.
 |
| 1. Get local community support to change the negative perception of management authorities.
 |
| 1. DPAW to manage the lake by reducing the threat of fires and water draw downs.
 |
| 1. Ramsar criteria should be applied, and ecological water requirements implemented as when originally studied.
 |
| 1. Monitor water quality from surrounding land-use and include as a condition of subdivision of lots.
 |
| 1. Work closely with DPAW and DOW to achieve measurable outcomes of management.
 |
| 1. Reporting to Commonwealth of possible change in ecological character could result in an intra-agency committee with the community.
 |
| 1. Response plan: work with development proponents in drainage design; review limits of acceptable change as preliminary assessment; work with COA to direct drainage through James Drain.
 |
| 1. Review the limits of acceptable hydrological change.
 |

**Supplementary Table 6.** Ecological processes within the spatial zones of Forrestdale Lake under a drying climate from: literature review, stakeholder interviews, and analysis of model cross-sections of the wetland (hydrology).

|  |  |
| --- | --- |
|  | **Wetland spatial zone** |
| **Information for the conceptual eco-hydrological model** | **Deep water** | **Inter-mediate** | **Dry buffer** |
| *Hydrology* |  |  |  |
| 1. Depending on high groundwater levels and rainfall.
2. Reduced groundwater and surface water connection to feed surface water.
3. Reduced groundwater due to garden bores adjacent to the wetland dry zone.
4. Area does not dry during summer (without consecutive dry years).
5. Muddy shorelines provide feeding habitat for migratory and wading birds and becomes dry after drawdowns.
6. Increased invasive flora species (e.g. *Typha orientalis*) with low water levels (consecutive years).
7. Increase risk of fires after consecutive dry periods.
8. Mosquitoes’ breeding cycle is interrupted after more than 3 consecutive dry months.
9. Exposure of acid sulphate soils after more than 6 consecutive dry months increases the risk of acidification.
10. The clay layer under the lake bed limits vertical conductivity and groundwater-surface water exchange is limited.

*Species composition and ecological responses*  | XXXXXXX | XXXX | XX |
| 1. Feeding habitat for migratory and wading birds.
 |  | X |  |
| 1. Resting and breeding habitat for waterbirds.
 |  | X |  |
| 1. Increase of invasive flora (e.g. *Typha orientalis*) limit feeding habitat of migratory and wading birds after drawdowns.
 |  | X |  |
| 1. Foxes reach nesting and resting places of waterbirds and freshwater turtles.
 |  | X | X |
| 1. Increase of breeding habitat for waterbirds with more fringing vegetation after consecutive dry periods.
 |  | X |  |
| 1. Decrease of feeding habitat for waterbirds with less surface water availability after consecutive dry periods.
 | X |  |  |
| 1. Decrease of habitat for aquatic invertebrates, macrophytes, and tortoises after drawdowns.
 | X |  |  |
| 1. Aestivating of freshwater turtles is limited in summer after consecutive dry periods.
 | X | X |  |
| 1. Migratory birds arrive in early summer.
 |  | X |  |
| 1. Migratory birds leave in early spring, however, the duration around the wetland is shorter after extensive dry periods.
 |  | X |  |
| 1. Waterbirds numbers and species composition have remained stable around 10.000 over the last 30 years. It is expected that the lake provided a number over 15.000 prior to the 1950s when water depth reached 2 m.

*Hydrological model* | X |  |  |
| 1. Groundwater moves upwards after winter rainfall and reverses downwards at the end of winter.
 | X | X | X |
| 1. Deeper groundwater moves from east to west and drops further around deep groundwater bores east of the lake.
 | X | X | X |
| 1. Precipitation and evapotranspiration influence surface- and groundwater availability in the lake’s ecosystem.
 | X | X |  |
| 1. In the past 25 years the lake has endured an increase of frequency and duration of consecutive dry periods.
 | X | X |  |
| 1. In the past 25 years the start of dry periods has moved from March (early autumn) to October (late spring).
 | X | X |  |
| 1. Hydrological gradient from east to west with deep water in the east of the wetland.
 | X | X | X |
| 1. Groundwater abstraction has increased over time, however only estimations exist from garden bores.
 | X | X | X |
| 1. Seasonal drying of the lake remained with a saturated lakebed in summer until the early 2000s; frequency of dry lake beds increases and remains within 3x (consecutive period of 3 months) within 5 years.
 |  | X |  |
| 1. Precipitation during winter has decreased while evapotranspiration losses have increased due to higher temperatures.
 | X | X | X |
| 1. Groundwater table remained above the stratigraphic layer (0.5 m below ground surface) capable of providing water to surface organics through capillary rise during summer until the 2000s.
 |  | X |  |

**Supplementary Table 7.** Proposed adaptation measures for groundwater and land-use management with indicated how each measure was assessed. Information from the eco-hydrological model and surface-groundwater model are: 1. Primary process; 2. Secondary process (indirectly informed after hydrological modelling); - not assessed.

|  | **Information source** |
| --- | --- |
| **Adaptation measure** | **Ecosystem model** | **Hydrological Model** | **Indirect** | **Decision process** |
| 1. Recoup unused entitlements (especially in groundwater capture zone of wetland).
 | - | 2 | X | X |
| 1. Restrict exempt use (especially in groundwater capture zone of wetland).
 | - | 2 | X | X |
| 1. Improve metering of licenses around the lake.
 | - | - | - | X |
| 1. Recover licenses through land-use change.
 | - | 2 | X | X |
| 1. Reduce Leederville aquifer abstraction.
 | - | 1 | - | X |
| 1. Implementing WSUD to redirect stormwater to lake from new developments around the lake.
 | - | 2 | X | X |
| 1. Sewer system to replace septic tanks.
 | - | - | - | X |
| 1. Get local community support to change the negative perception of management authorities.
 | 1 | - | - | X |
| 1. DPAW to manage the lake by reducing the threat of fires and water draw downs.
 | 1 | 1 | - | X |
| 1. Ramsar criteria should be applied, and ecological water requirements implemented as when originally studied.
 | 1 | - | - | X |
| 1. Monitor water quality from surrounding land-use and include as a condition of subdivision of lots.
 | - | - | - | X |
| 1. Work closely with DPAW and DOW to achieve measurable outcomes of management.
 | 1 | - | - | X |
| 1. Reporting to Commonwealth of possible change in ecological character could result in an intra-agency committee with the community.
 | 1 | - | - | X |
| 1. Response plan: work with development proponents in drainage design; review limits of acceptable change as preliminary assessment; work with COA to direct drainage through James Drain.
 | 1 | - | - | X |
| 1. Review the limits of acceptable hydrological change.
 | 1 | 2 | - | X |