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Identifying key dynamics and ideal governance structures for successful ecological management

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ABSTRACT

Estuaries around the world are often degraded and subject to issues surrounding effective management and governance. Without substantial changes in the overall management of many catchments, there is a risk that estuarine health will further decline, causing serious social and economic impacts. The Peel region is one of Australia's fastest growing residential areas and the social and economic wellbeing of the local community is tied to the health of the Peel–Harvey estuary. This estuary is the largest in south Western Australia and has for decades incurred considerable anthropogenic impacts. This study uses the Peel–Harvey estuary as a case study for the assessment of governance structures and ecosystem dynamics using qualitative models. Each model highlights drivers that impact the most important assets, water quality and general environmental quality. Potential management strategies are identified to tackle ineffective monitoring and regulation of impacts, overlapping responsibilities between different public infrastructure providers, and a lack of accountability. Incorporating 'ideal' management strategies into 'future' models clarified paths of governance and provided better delivery of outcomes. Strong environmental and nutrient management were integral to effective environmental governance, as was the need for whole-of-government environmental decisions to be made in the context of predicted longer-term benefits for all sectors, including the general community. The assessment of social–ecological structures, issues and potential management strategies using qualitative models identified mechanisms to achieve effective management and resulted in predictions of increased environmental quality, as well as increased social and economic values.

1. Introduction

Catchments worldwide are subject to multiple and interrelated impacts that typically require remedial management intervention, but are often managed by quite disconnected agencies. Ensuring appropriate governance structures for the facilitation of improvements in catchments and estuaries is critical and can be achieved by creating linkages for cooperation and mutual accountability at both local and higher levels. Furthermore, effective links between resource users and public infrastructure providers are critical to increase the

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robustness of these social–ecological systems (Anderies et al., 2004). However, the initial alteration of governance structures may be a turbulent and arduous process (Mitchell and Hollick, 1993). Some successful examples include the management of Chesapeake Bay (Hennessey, 1994) and the Johnston River catchment in Queensland (Margerum, 1999), where steps towards integrated adaptive management, including alterations to governance, have been achieved. Similarly, because the majority of rivers in south-west Western Australia are in poor condition (Halse et al., 2002), these also require substantial long-term alterations to management if their health, as well as reliant social and economic systems, are to be improved. This study uses a qualitative modelling approach to identify key drivers of ongoing anthropogenic impacts and governance dynamics that, if modified, could shift these systems away from being dysfunctional and maladaptive to being functional and effective.

The Peel–Harvey estuarine system (Fig. 1) has been formally recognised as the most at-risk estuary (excluding freshwater environments) in Western Australia (Department of Fisheries, 2011). The surrounding area is one of the fastest growing regions in Australia (Department of Environment and Heritage, 2006). The rate of population growth and degradation for this estuary has similarities with many others globally (*e.g.*, Lotze et al., 2006); we have therefore used it as a case study for the modelling and identification of mechanisms for improving governance. Residential land-use in the area is replacing agricultural and industrial land-use and recreational uses and the visual amenity of the estuary is highly valued for maintaining real estate values and tourism. In addition, wetlands of international importance, as recognised by the Ramsar Convention on Wetlands, are located within the Peel–Harvey region and international agreements include an obligation for their protection. For these reasons, the ecological health of the estuary is of high social and economic importance.

Estuarine health is an issue in the Peel–Harvey region as increased macroalgal volume and toxic algal growth (Department of Water, 2011) has lead to suggestions that the estuary may be shifting to a eutrophic state (Rogers et al., 2010). This is concerning given issues caused by eutrophication between 1960 and 1994; extreme levels of macroalgal growth, toxic algal blooms (*Nodularia* spp.) and large accumulations of algal wrack were observed around the estuary which stimulated public complaints to local councils (Atkins et al., 1993) and was partly responsible for a depression of real estate values (McComb and Davis, 1993). In response to these concerns, the state government constructed an artificial entrance, the Dawseville Cut (Fig. 1), to increase tidal flushing of the estuary in 1994 (Brearley, 2005).

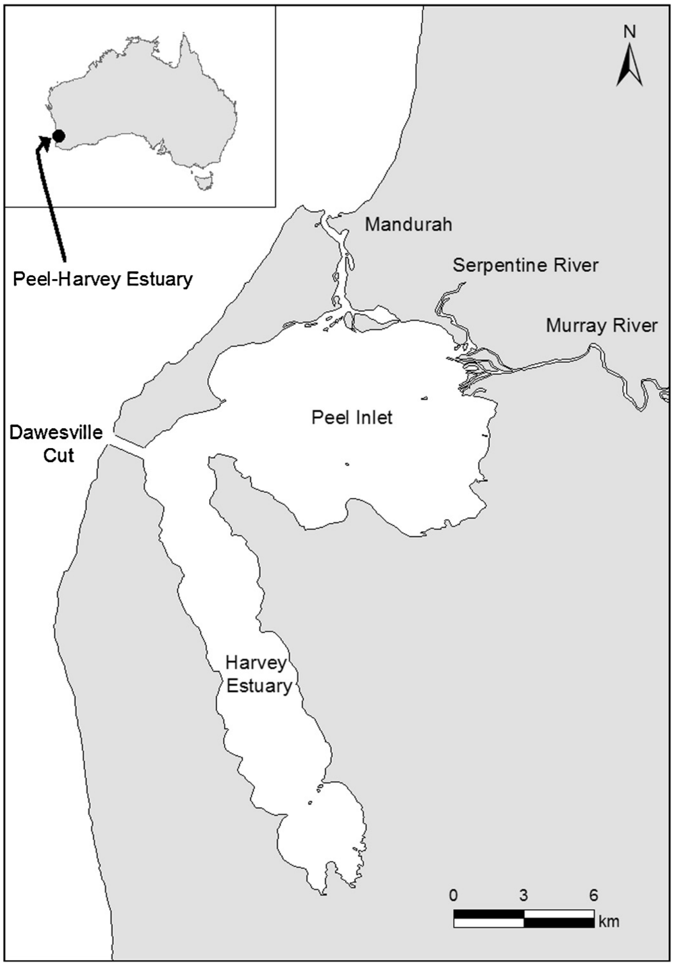

Fig. 1 – Peel–Harvey estuarine region, which includes Peel Inlet and the Harvey estuary.

After the opening of the Dawseville Cut in 1994, residential development in the region increased dramatically. Real estate speculation was high (Gilles et al., 2004) and greatly increased property values. Strategies to reduce nutrient input from the catchment were intended to be implemented when the Dawseville Cut was opened; however, there has been no evidence that nutrient inputs have declined (Hale and Butcher, 2007). There has also been a gradual loss of wetlands from the estuary as a result of land reclamation, clearing for livestock and other developments (Van Gool et al., 2000). Moreover, there is evidence that fish communities are returning to the status observed when the estuary was highly eutrophied, prior to the Dawseville Cut (S. Hoeksema and P. Coulson, pers. comm.). While these issues regarding the health of the estuary have been widely recognised (Rogers et al., 2010; Peel–Harvey Catchment Council, 2011), there have been no management interventions to effectively address them.

Similar to the theory behind mechanism design in economics (Maskin, 2008), a central aim of this project is to identify the desired goal for the management of the system using stakeholder input, followed by an assessment of the mechanisms through which the goal can be achieved. The use of scenarios to assess different mechanisms is undertaken as they can cope with the complexity and uncertainty associated with social–ecological systems and multiple potential adaptation strategies (Berkhout and Hertin, 2000). An additional aim is to identify the key issues and drivers of governance contributing to the current inability to achieve the goal as well as to develop a holistic understanding of governance structures. As suggested, to be relevant to the assessment of governance in social–ecological systems (Anderies et al., 2004), we have incorporated both resource-users and public infrastructure providers into the models. Their inclusion allows the integrated assessment of dynamics, flow between different components of the system and barriers to effective governance. In order to cope with a lack of quantitative data and to allow the assessment of multiple scenarios, qualitative models (Levins, 1974; Puccia and Levins, 1985) were developed based on stakeholder knowledge and perceptions of the whole system. Stakeholders were used to assist in the identification of information previously unknown to researchers (Kalaugher et al., 2012) and the scale of complexity most relevant for applied management (Berkhout et al., 2001). Furthermore, stakeholder involvement increases the likelihood of uptake of conclusions given participation and agreement on model structure (Phillipson et al., 2012).

The representation of governance can be problematic in models as it may involve numerous 'actors' such as different government departments and agencies, community groups and the general public, all of which usually have their own objectives and mandates. Analysing the dynamics of resource users and public infrastructure providers in cohesive models is essential for the assessment of social–ecological systems such as catchments and estuaries (Anderies et al., 2004). Hence, the models developed in this study incorporate both groups and assess the likely effectiveness of strategies to improve the sustainability of ecological, social and economic assets that are reliant on the health of the Peel–Harvey estuary.

2. Methods

We used qualitative models initially to 'map' stakeholder perceptions of the governance structure for the Peel–Harvey system. This technique does not require precise quantitative data and can therefore be used in data-limited situations to include non-quantifiable components. Following this, the technique was used to provide predictions of response to perturbations which can be calculated by using feedbacks between system components (Dambacher et al., 2002). In contrast to quantitative models that predict the magnitude of change, these models are designed to predict the direction of change, increase the understanding of current and future dynamics, and identify key factors impacting system stability (Bodini et al., 2000). They are particularly useful in adaptation planning in various fields including natural resource management or social (including governance) and economic problems (Dambacher et al., 2007; Metcalf et al., 2010). For instance, issues or barriers to future goals can be highlighted through qualitative model production and analysis. Potential adaptation strategies or 'ideal' management scenarios can then be identified by removing barriers within the model structure (*i.e.*, removing links or variables contributing to the undesired response). Finally, the reliability of predictions and the likelihood of the system shifting to an alternate state can be assessed using qualitative model stability (Dambacher et al., 2003). This is important because stable systems offer greater predictability and therefore reliability of management interventions.

2.1. Stakeholder workshops and model production

Two stakeholder workshops were undertaken involving a total of 42 participants from a range of backgrounds and agencies (*e.g.*, government departments, local conservation group, fishing interest groups and universities). During these workshops, stakeholders provided information to link ecological, management and governance components within the Peel–Harvey system. High priority assets were first identified which resulted in a range of different assets according to stakeholder background and knowledge. The stakeholders were then asked to rank all identified assets and determine the highest priorities. As stakeholders were from a range of backgrounds and all were encouraged to participate, the final ranking of assets was deemed to be valid. Water quality, defined as water of a condition suitable for recreational activities such as swimming, fishing and boating, was identified as one of the highest priorities. General environmental quality and ecosystem health were also identified as high priorities. The improvement of these assets through management and governance was identified as the goal to be achieved through qualitative modelling.

Qualitative models were elicited by drawing interactions between aspects of the ecological system, its physical and economic drivers, and associated management and governance structures. Variables and their interactions, which form the basis of the qualitative models, were determined during the workshops using expert (stakeholder) opinion and knowledge. For example, questions such as "What affects

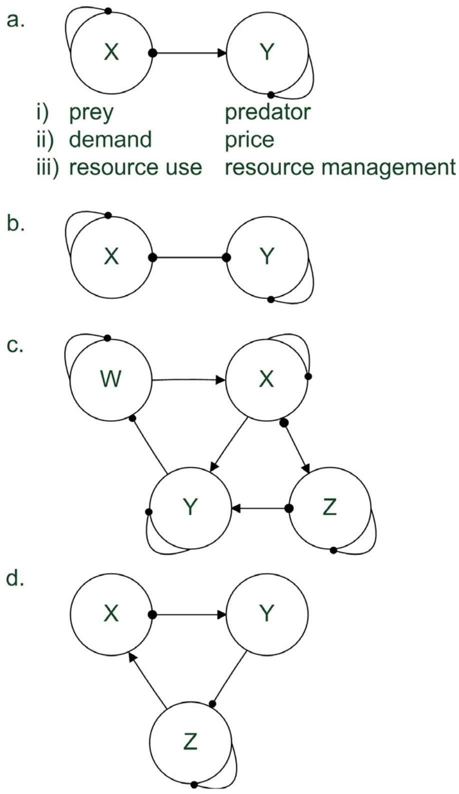

Fig. 2 – Example signed digraphs of (a) a sign stable system, class I systems with (b) two and (c) four variables, and (d) a three variable class II system. Links between variables denote the sign of negative (•——) and positive (→) direct effects. Links starting and ending in the same variable denote self-effects, which represent a reliance on factors external to the modelled system or density dependent growth; see text for additional explanation.

water quality in the Peel Harvey estuary", "How is water quality affected by X" and "What actions are undertaken to manage and improve water/environmental quality" were asked. Responses were immediately translated into models (or signed digraphs, see below) on a whiteboard and stakeholders were encouraged to comment and alter the digraphs as they were being drawn to ensure they accurately represented their opinions of the system. Digraphs were refined through an iterative process of repeated workshops and comments from representatives of management agencies to ensure that the views obtained were representative of the broader stakeholder community.

Qualitative models are produced using sign directed graphs, or signed digraphs, which are constructed according to the signs (positive or negative) of interactions between variables (*e.g.*, Levins, 1974; Puccia and Levins, 1985; Dambacher et al., 2002). Sign digraphs can be used to represent systems with diverse types of components, including biological, physical, economic and governance. For instance, in Fig. 2a variable X has a positive direct effect on variable Y (•——), which in turn has a negative direct effect on X (←). This basic interaction describes a negative feedback system that can be used to represent the dynamics of predators and their prey, consumer demand and product price, or the regulation of resource use by a management agency. Negative self-effects (↻) are used to represent intraspecific limitations to population growth, or reliance on factors that are external to the modelled system, such as density dependent growth, or the statutory obligations of an agency.

While signed digraphs provide a convenient means to describe the interactions in a system and elicit expert knowledge, there is also a corresponding formalization through a system of equations:

$$\frac{dN_i}{dt} = g_i(N_1, N_2, \ldots N_n; \quad p_1, p_2, \ldots p_m), \tag{1}$$

where there are n number of variables N_i, and p_m are constant parameters. At equilibrium the growth function $g_i = 0$ for all variables. By differentiating Eq. (1) with respect to each variable,

$$\frac{\partial g_i}{\partial N_j} = a_{ij} \tag{2}$$

we obtain the elements of the Jacobian matrix **A**, which details the direct interactions between variables (*i.e.*, where a_{ij} represents the direct effect of variable N_j on variable N_i). The Jacobian matrix for the model of Fig. 2a

$$\mathbf{A} = \begin{bmatrix} -a_{XX} & -a_{XY} \\ a_{YX} & -a_{YY} \end{bmatrix}, \tag{3}$$

is an equivalent representation of the sign digraph, where matrix elements correspond to the individual graph links. For example, the only positive element in Eq. (3) equates to the positive link to Y from X.

A signed digraph, and its corresponding Jacobian matrix can be used to assess a system's stability (*i.e.*, can a system return to a former equilibrium following a short-term shock or disturbance), and predict how its variables will respond to a sustained perturbation or input due to a change in a parameter (*i.e.*, will variables increase or decrease if the system is pushed to a new equilibrium). Qualitative assessments of stability and perturbation response both rely on examination of system feedback, and proceed either by analysis of signed digraphs (Puccia and Levins, 1985) or mathematical operations on the matrix **A** (Dambacher et al., 2002, 2003). In this work we use the methods of Dambacher et al. to analyse parameters for model stability (Section 2.2) and calculate predictions of response to perturbation (Section 2.3). We present a general overview of qualitative modelling methods, which can be supplemented with more detailed and technical presentations in the above cited references, http://www.ent.orst.edu/loop/default.aspx, and Supplement 1 of Dambacher et al. (2002) in *Ecological Archives* E083-022-S1 at http://www.esapubs.org/archive/.

2.2. *Assessment of model stability*

Stability generally depends on a system being adequately regulated by negative feedback cycles, such that any perturbation to the system results in a return to its previous state or equilibrium. Qualitative model stability is formally assessed according to the Routh–Hurwitz criteria, which determines whether the eigenvalues of **A** all have negative real parts (Puccia and Levins, 1985; Dambacher et al., 2003). In a qualitative analysis, it is possible to determine whether a model is stable given any possible combination of interaction strengths in **A** (*i.e.*, sign stable model), or, if there are conditions by which it could be unstable (*i.e.*, conditionally stable model), whether these conditions make it prone to having excessive positive feedback (*i.e.*, class I model) or excessive higher-level feedback (*i.e.*, class II model) (Dambacher et al., 2003).

The relative stability of class I models requires that the overall feedback, or determinant (det) of **A**, is negative – *i.e.*, $-1^{n+1}\det(\mathbf{A}) < 0$, where n is number of variables in the system or size of **A**, and the multiplier -1^{n+1} maintains a sign convention for even and odd sized systems. The model in Fig. 2b is a class I model with overall feedback equal to $a_{XY}a_{YX} - a_{XX}a_{YY}$, thus the system will be unstable when the positive feedback cycle is too strong, such that $a_{XY}a_{YX} > a_{XX}a_{YY}$. When a class I system that is unstable is perturbed, the strong positive feedback tends to amplify the perturbation and move the system away from its former state. This departure can eventually lead to the demise or extinction of a variable, and possibly the attainment of a new and different equilibrium. The potential stability of class I models can be scaled by the relative number of positive and negative cycles in its overall or highest level of feedback. Weighted feedback, wF_n, is calculated as a ratio of the net to total number of terms in the overall feedback of a system. For the overall feedback of the model in Fig. 2b, a single positive and a single negative feedback cycle sum to zero with a divisor of two, giving a weighted feedback value of zero. The model in Fig. 2c is also a class I model with overall feedback having five negative cycles and one positive cycle (*i.e.*,$-a_{WW}a_{XX}a_{YY}a_{ZZ} - a_{WW}a_{XX}a_{YZ}a_{ZY} - a_{WW}a_{ZX}a_{XZ}a_{YY} - a_{XW}a_{YX}a_{WY}a_{ZZ} - a_{XW}a_{ZX}a_{WY}a_{YZ} + a_{WW}a_{YX}a_{XZ}a_{ZY}$), giving it a weighted feedback value of -0.67.

Values of wF_n can range between -1 and +1, where a value near +1 describes a system where nearly all feedback cycles are positive, a value near -1 indicates nearly all feedback cycles are negative, and a value near 0 indicates a nearly equal balance of positive and negative cycles. Simulation studies by Dambacher et al. (2003) tested wF_n as a means to assess potential model stability, and found class I models with $wF_n > 0$ to have a low potential for stability (*i.e.*, less than 50% chance of being stable), and $wF_n < -0.5$ to have a relatively high potential for stability (*i.e.*, greater than 90% chance of stability).

Stability of class II models depends on a balance between long and short feedback cycles, such that feedback at lower levels of the system is greater than feedback at higher levels. A system that is dominated by higher-level feedback has the tendency to overcorrect, and will amplify a disturbance through oscillations with increasing amplitude. Assessing this balance between lower and higher levels of feedback first requires an accounting of feedback, F_n, at each of the n levels of the system; stability is then analyzed through a series of Routh–Hurwitz inequalities, the first of which is:

$$F_1F_2 + F_3 > 0, \tag{4}$$

where stability depends on a positive value. For the system of Fig. 2d, there are three levels of feedback, $F_1 = -a_{ZZ}$, $F_2 = -a_{XY}a_{YX}$, and $F_3 = -a_{XZ}a_{ZY}a_{YX} - a_{ZZ}a_{XY}a_{YX}$, all of which are negative. The product of F_1 and F_2, however, creates a term that is repeated with the opposite sign in F_3 and thus cancelled in the inequality of Eq. (4), giving it a negative value. Thus, despite an absence of positive feedback in this system, there is excessive higher-level feedback in F_3, and no combination of interaction strengths in **A** can produce a stable system. Similar to the above described metric of weighted feedback, one can calculate the ratio of the net to total number of terms in the Routh–Hurwitz inequalities, which provides the means to scale the relative stability of class II models. Systems with small or negative weighted values for the Routh–Hurwitz inequalities have a very low potential for stability and large positive values have a high potential for stability (Dambacher et al., 2003).

A signed digraph can be categorized as a class I or class II model based on consideration of two above described weighted metrics, which separately address the amount of positive overall feedback, and the balance between lower and higher levels of feedback. Class I models (*e.g.*, Fig. 2b and c) generally have small negative values or positive values for wF_n and large positive values for Routh–Hurwitz inequalities, and their relative potential for stability can be assessed by the metric of wF_n. Conversely, class II models (*e.g.*, Fig. 2d) generally have large negative wF_n values, and small positive values or negative values for the Routh–Hurwitz inequalities, and thus are prone to instability from excessive higher-level feedback. The stability properties of the models produced in this study are reported using the class of model and, if Class I, the wFn.

2.3. *Assessment of perturbation response*

A qualitative model can also be analysed to predict how a system will respond to a perturbation that enters the system by way of a change in a parameter that regulates the growth or level of activity of a variable. As a perturbation emanates from the affected variable it is transmitted along the direct and indirect pathways leading to the response variable. Predicting the qualitative direction of change (*i.e.*, +, $-$, 0) in the response variable requires an accounting of the total number of positive and negative effects transmitted through the system. For relatively small systems (*i.e.*, <7 variables), this can easily be accomplished through analysis of the signed digraph (Puccia and Levins, 1985). For instance, in the model of Fig. 2a, a positive input to variable X, say through a technological change that increases the rate of resource use, is transmitted along the positive link to Y, resulting in a heightened intensity of resource management. Conversely, an increase in public concern for the conservation of a resource will act as a positive input to Y that is transmitted along a negatively signed pathway to X, resulting in a decrease in resource use.

In larger and more complex systems, there can be a large number of direct and indirect pathways between input and response variables that transmit both positive and negative effects, which can make graphical analyses difficult. In such circumstances, one can calculate response predictions from mathematical operations on **A**. Here we are interested in the direction of change in the equilibrium level of each of the system variables ($\mathbf{N}^*$) due to a change in a parameter p_h, which is obtained by:

$$\frac{d\mathbf{N}^*}{dp_h} = -\mathbf{A}^{-1}\frac{\partial \mathbf{g}_i}{\partial p_h}. \tag{5}$$

Given the matrix equality:

$$-\mathbf{A}^{-1} = \frac{\mathrm{adj}(-\mathbf{A})}{\det(-\mathbf{A})}, \tag{6}$$

where "adj" is the classical adjoint, or adjoint matrix, Eq. (5) can be rewritten as:

$$d\mathbf{N}^* = \underbrace{\frac{1}{\det(-\mathbf{A})}}_{\text{overall feedback}} \underbrace{\mathrm{adj}(-\mathbf{A})}_{\text{relative response}} \underbrace{\frac{\partial \mathbf{g}_i}{\partial p_h}dp_h}_{\text{strength of input}}, \tag{7}$$

(Dambacher et al., 2005). The adjoint matrix summarizes the total number of direct and indirect effects transmitted between the input and response variables. As we are only interested in predicting the direction or sign of a response, the strength of the input can be ignored. Also, for stable systems, det(−A) is always positive, and thus the sign of predicted responses to a perturbation can be derived from the signs of the adjoint matrix elements. The predictions obtained from the adjoint matrix form a large part of the results reported in this study.

For the model system of Fig. 2c,

$$\mathrm{sgn}(\mathrm{adj}(-\mathbf{A})) = \begin{array}{c} \\ \mathrm{W} \\ \mathrm{X} \\ \mathrm{Y} \\ \mathrm{Z} \end{array} \begin{array}{c} \begin{array}{cccc} \mathrm{W} & \mathrm{X} & \mathrm{Y} & \mathrm{Z} \end{array} \\ \begin{bmatrix} + & - & - & ? \\ + & + & ? & - \\ + & + & + & ? \\ ? & ? & - & + \end{bmatrix} \end{array}, \tag{8}$$

the sign (sgn) of eleven of the response predictions is completely determined, while five are ambiguous (?). Inputs to the system are read down the columns and responses along the rows. Thus a positive input to variable X is predicted to decrease the level of W and increase Y, while the response of Z is qualitatively ambiguous due to both a positive and negative pathway connecting it to X.

2.4. *Modelling scenarios*

Here we report the digraph (model) structure produced by stakeholders during the workshops which focus on the management and governance of water and environmental quality in the Peel–Harvey estuary. Following initial model construction and subsequent digraph iterations with stakeholders, perturbations to the modelled systems were analysed using the matrix operations described above. Predictions of the response to perturbation and model stability were assessed to determine adaptation strategies that may improve the management of water and environmental quality.

Current governance structures are described at an operational or localised level (Local Governance Model) and at a higher level (High Level Governance Model). Both models include resource users and public infrastructure providers such as Government departments and agencies that manage different aspects of the Peel–Harvey system. Direct and indirect impacts on water and environmental quality are identified and linked to departments and agencies according to their management and regulatory roles. Workshop participants offered differing perceptions on the effectiveness of current management and governance structures and, in order to represent these differences, two versions of both the Local Governance and the High Level Governance Model are reported (Table 1). Strong-link models represent the scenario where expected (*i.e.*, legislated) management actions are highly effective, collaboration between and accountability of departments and agencies is high, and government decisions that result in beneficial outcomes for water quality and the environment are strong. That is, decisions persist regardless of external pressure to remove them. Weak-link models represent the opposite scenario, where expected management actions, collaborations and accountability are nonexistent, inconsistent or ineffective.

The investigation of various management issues and 'ideal' management strategies that improve water or environmental quality is undertaken through the analysis of the qualitative models. 'Ideal' scenarios are considered to be those that improve model stability (see description of qualitative modelling methods) and achieve a desirable outcome (*i.e.*, an improvement in water quality or environmental quality). These 'ideal' strategies are essentially

Table 1 – The level of governance assessed and the different versions of the models produced in the study. Different levels of governance (local and high level) were assessed to allow the investigation of processes occurring at all levels. Different versions of models were produced to ensure all workshop participants' perceptions were represented and that future management strategies could be identified.

Governance level	Model versions	Participant perceptions represented
Local level (operational level)	Strong-link local level model (current situation)	Strong and effective management actions, collaboration, accountability and eco-government decisions
	Weak-link local level model (current situation)	Weak and ineffective management actions, collaboration, accountability and eco-government decisions
	Future local level model	Perceptions and management strategies that provided the most ideal outcome for stability and asset management
High level (broader community and governmental level)	Strong-link high level model (current situation)	Strong and effective management actions, collaboration, accountability and eco-government decisions
	Weak-link high level model (current situation)	Weak and ineffective management actions, collaboration, accountability and eco-government decisions
	Future high level model	Perceptions and management strategies that provided the best outcome for stability and asset management

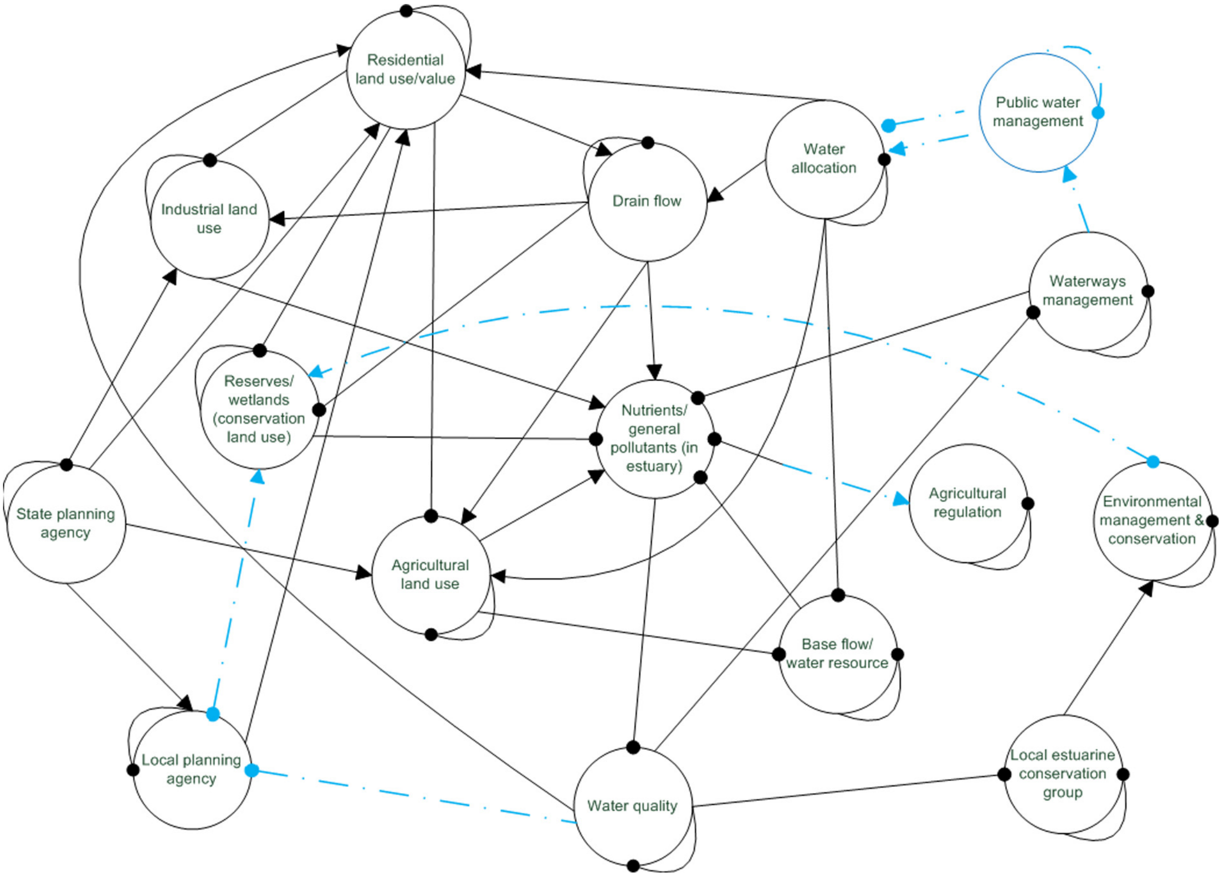

Fig. 3 – Structure of the two Local governance models (current situation). Model structures have been shown on one figure to easily display differences between the Strong-link model (includes dashed lines and black lines) and those included in the Weak-link model (black lines only). Strong- and weak-link models were analysed separately. Two possible links have been assessed between *Public water management* and *Water allocation*.

models of a putative 'future' and are incorporated into future models (Table 1) to assess the impact of removing issues and structural barriers to achieving improved water and environmental quality. All variable names are shown in italics for clarity.

2.4.1. *Local governance structure*

2.4.1.1. *Current models*. Impacts on water quality, including management actions, are included in both the strong- and weak-link local governance models (Fig. 3). Definitions and roles of variables are reported in Table 2.

The link from *Public water management* to *Water allocation* can be either positive or negative depending on the situation at hand. Approvals for the sale of water by the *Water allocation* variable may be given, renegotiated (positive links), or declined (negative link) by *Public water management*. A positive link between agencies or departments represents approvals or assistance (+) from one department to facilitate work in another department (+) and can also represent the alignment of policies regarding management of the estuary. In contrast, a negative link between agencies or departments represents the situation where increased action (+) by one government department reduces activities occurring in a related agency (–) or vice versa.

2.4.1.2. *Future model*. Issues with stability, overlapping jurisdictions, mutual accountability and the need to improve water quality (see Section 3 for evidence) are addressed through alterations to model structure in the future model (Fig. 4a). Specific structural changes include the removal of links representing nutrient input and the use of water by agriculture and industry (orange dashed lines, Fig. 4a). This does not signify that nutrient input and use of base flow no longer occurs, rather that the placement of additional regulations determine that nutrient input and use of base flow cannot increase. In addition, the links from *Water quality* to the *Local planning agency*, and those between the *Local planning agency* and *Reserves/wetlands* no longer exist.

New links in the future model are from the *Local estuarine conservation group* to *Environmental management & Conservation*, *Agricultural regulation* and *Waterways management* (blue dashed lines, Fig. 4a). The negative link from *Public water management* to *Water allocation* is retained.

2.4.2. *High level governance structure*

2.4.2.1. *Current models*. The High level governance models (Fig. 5) are used to assess the dynamics associated with broad-scale estuarine (environmental) management rather than

Table 2 – Variable description, definition and role for the Local governance models. The role of variables in the Strong link model (dashed lines, Fig. 3) has been described as this includes links from both the Strong and Weak link models.

Variable name	Definition	Role (Strong link models)
Water quality	Quality of estuarine water for ecological and recreational (i.e. boating, fishing) use	Good water quality increases residential land values
Nutrients/general pollutants	Waste products from run-off as well as residential, agricultural and industrial land use	Reduces water quality
Base flow water resource	Freshwater inflow from rainfall and aquifers	Flows into the estuary and reduces nutrient concentrations
Reserves/wetlands	Conservation areas and undeveloped land adjacent to the estuary	Reduces nutrient concentrations by filtering and storing nutrients
Drain flow	Engineered drainage and flow of water and waste from various inputs	Increases nutrient concentrations in estuarine waters, and reducing flooding which reduces wetland sustainability and allows industrial land use
Public water management	Responsible for planning and allocation of water use to private businesses	Increases or decreases allocation, depending on advice from various parties including *Waterways management*
Waterways management	Responsible for water quality management	Monitors estuarine water quality, acts to reduce nutrient input and provides advice on appropriate water allocations
Local estuarine conservation group	Small group working to improve estuarine health	Monitors water quality and informs *Environmental management & conservation* if water quality declines
Environmental management & conservation	Management agency responsible for managing the environment	Improves and maintains effective reserves, wetlands and conservation areas around the estuary
Agricultural regulation	Agency responsible for managing agricultural waste products	Monitors and reduces agricultural nutrient inputs
Water allocation	Amount of water available for all usage types	Reduces base flow while increasing drain flow and capacity for residential and agricultural land use
Local planning agency	Agency responsible for development and management of land use in local area	Monitors water quality and wetlands and enables increased development and residential land use
State planning agency	Responsible for statewide development	Allows agricultural and industrial land use and encourages local development approvals
Agricultural land use	Use of land for agricultural purposes	Uses base flow for irrigation etc. and inputs estuarine nutrients into waters flowing into the estuary
Residential land use/value	Use of land for residential purposes	Is allocated water and increases estuarine nutrient input through runoff from impervious surfaces, fertiliser use etc.
Industrial land use	Use of land for industrial purposes	Increases estuarine nutrient input through waste products

direct management of water quality as in the Local governance models. Descriptions, definitions and roles of variables are reported in Table 3. The strong-link high level governance model contains links between *Eco-Government decisions* (commitment to improve the environment) and the *Resource management/protection agencies*. In contrast, the weak-link model does not possess these links to represent the alternative perception, that these relationships are ineffective for the overall management of the Peel–Harvey estuary.

2.4.2.2. Future model. A number of alterations are included in the future models (dashed blue lines, Fig. 6) in response to issues identified in the current models. First, links to represent the strong and consistent monitoring and rehabilitation of *Environmental quality* by *Resource management/protection agencies* are included. Second, a negative link from the *Economic value of the environment* to *Eco-Government decisions* is included to represent actions by Government to improve the environment, in response to a decline in economic value. Third, a negative link from *Eco-Government decisions* to *Total resource use* is used to represent actions such as the implementation of new legislation, to reduce resource use.

In addition, to increase the stability of the model, the link to *Resource management/protection agencies* from *Eco-Government decisions* and other links to *Eco-Government decisions* are changed to remove the perceived direct influence of the development sectors on environmental decisions (orange lines, Fig. 6).

3. Results

3.1. *Local governance structure*

3.1.1. *Current models*

The weak-links model is a class II system with a very low potential for stability, which is caused by high-level (*i.e.*, long) feedback cycles, and must be addressed in the future model to ensure reliability of results and stability of management actions. The instability is caused by the weak and non-existent management of nutrient inputs and water quality. For example, no link exists between *Public water management* and *Water quality* as stakeholders suggested there are no effective management actions undertaken by this agency to improve estuarine water quality.

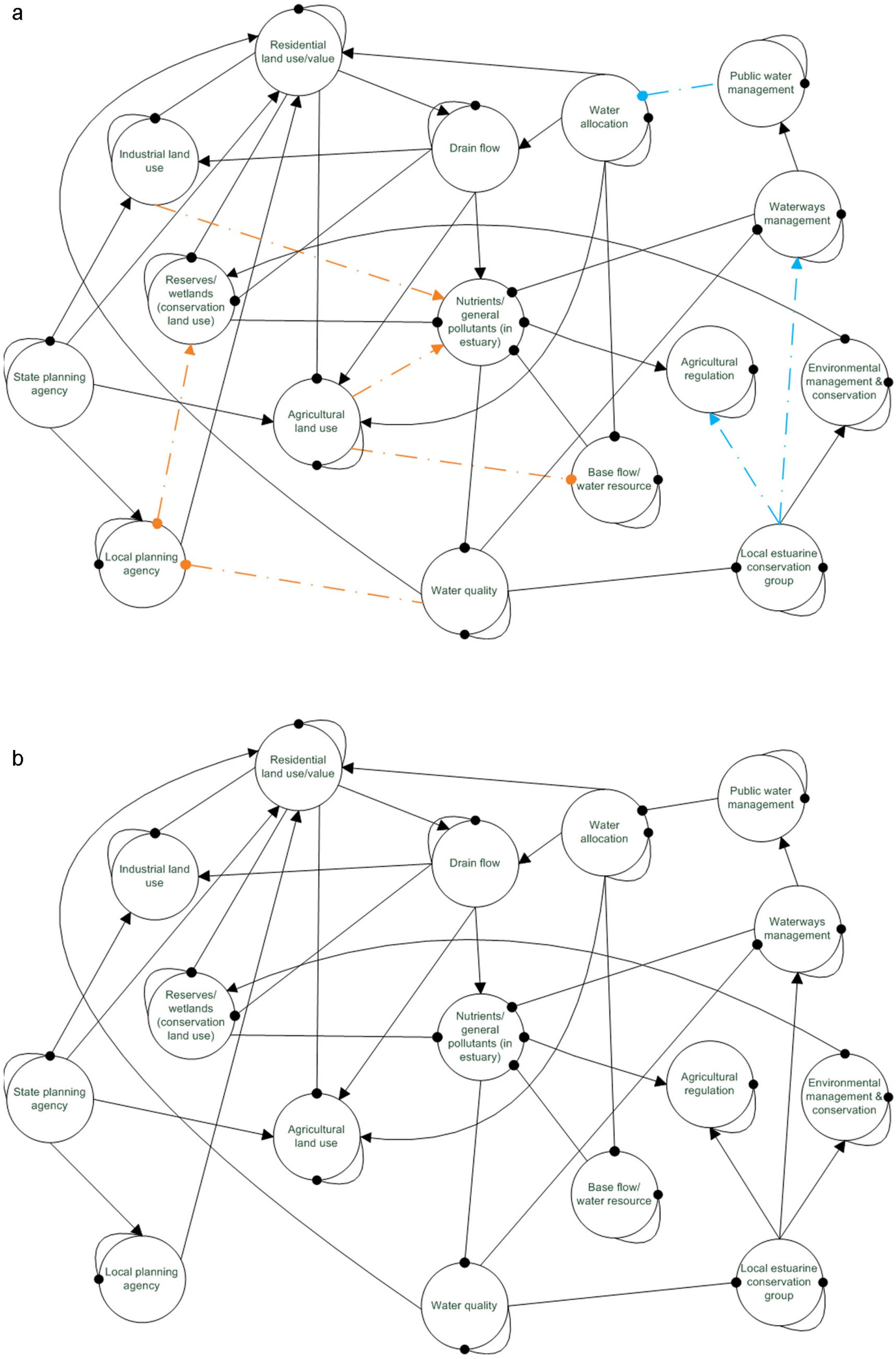

Fig. 4 – Future local governance model where (a) highlights links that were included (blue dashed links) and removed (orange dashed links) from Fig. 3 while (b) shows the final future local governance model.

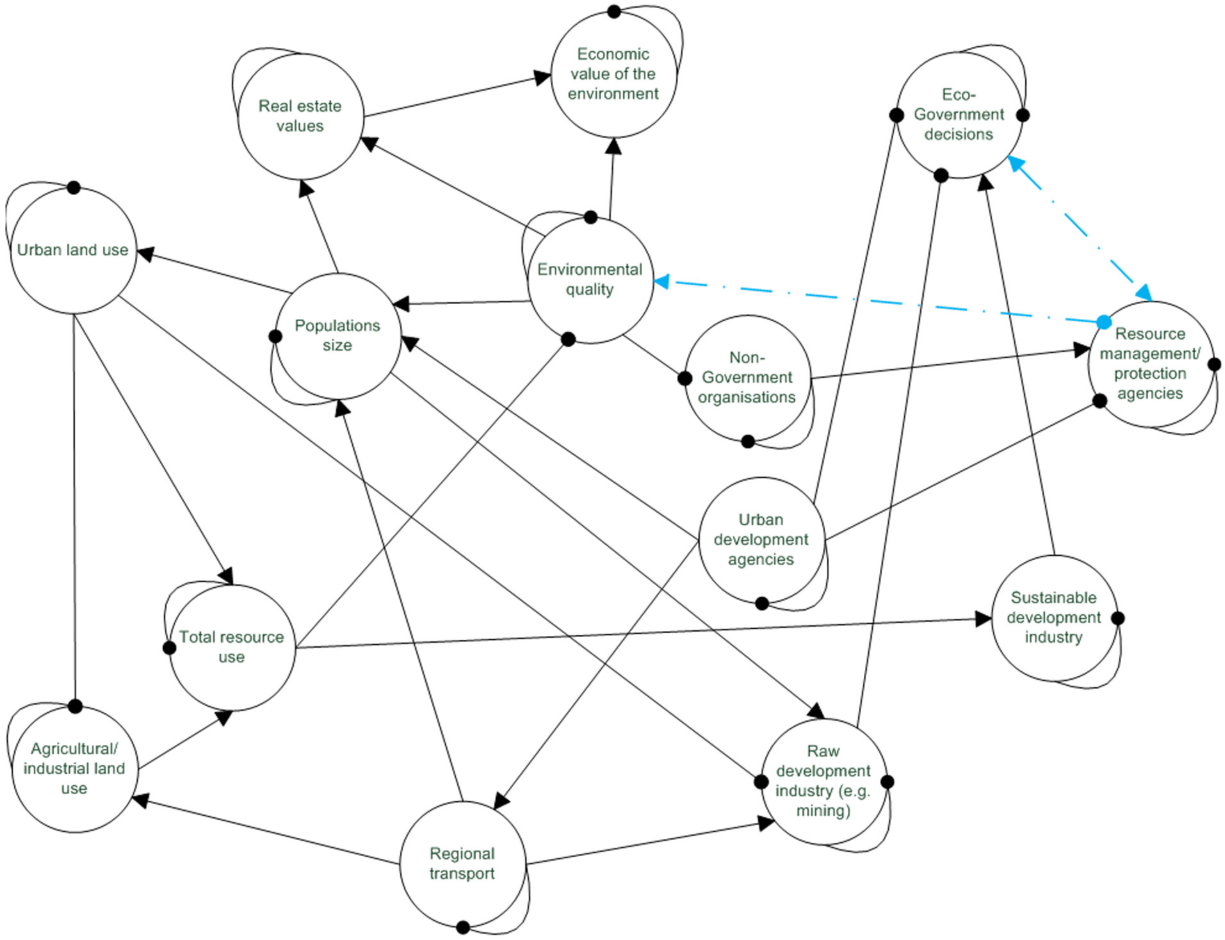

Fig. 5 – High level governance model (current situation) including links used in the strong-links model (blue dashed lines). The dashed links were removed for the weak-links model.

The strong-link model is also class II system with a very low potential for stability, regardless of the link from *Public water management* to *Water allocation* (Fig. 3). The presence of a positive or negative link between these variables determines the effectiveness of water quality management. The model with a positive link predicted *Water quality* will decline following an increase in activity by *Public water management*. This result is non-intuitive and occurs due to multiple indirect paths including variables that increase *Drain flow*, *Residential land use* and *Nutrients/general pollutants*. In contrast, when *Water allocation* is negatively impacted by *Public water management*, *Water quality* was predicted to increase.

Both current (strong- and weak-link) local governance models (Fig. 3) have departments and agencies with overlapping jurisdictions for the management of water quality, according to stakeholder input during model production. Overlapping variables include the *Local planning agency*, *Public water management* and *Waterways management*. This overlap is seen in Figure 3 through negative links from *Water quality* to these departments/agencies to represent monitoring, in addition to links from these agencies to other variables representing direct actions to improve water quality, such as a reduction in nutrients entering the estuary. The *Local estuarine conservation group* is also linked to *Water quality*, however, this interaction is in the form of water quality monitoring alone as this group does not have the authority to remediate water quality.

Issues with accountability can be seen through the comparison of departmental and management agency actions in both models. For example, *Waterways management* is included in both models and represents actions to protect and conserve freshwater and estuarine environments. *Waterways management* is expected by stakeholders to have a direct influence on *Public water management* where planning and use of water are determined. However, the diversity of views on the effectiveness of existing interactions with *Waterways management* and of the management influence of *Public water management* on *Water allocation* determine that *Public water management* is only included in the strong-link model. If accountability was obvious, as in the Strong links model, there would be no diversity of views on the existence of links between *Public water management* and *Waterways management* or the actions taken regarding the allocation of water resources.

3.1.2. *Future model*

In the future models, there was a small increase in the potential stability of the system due to the removal of links

Table 3 – Variable description, definition and role for the High level governance models. The role of variables in the Strong link model (dashed lines, Fig. 5) has been described as this includes links from both the Strong and Weak link models.

Variable name	Definition	Role (Strong link models)
Environmental quality	Environmental quality for supporting biodiversity, ecosystem structure and function	Good environmental quality improves real estate values and the economic value of the environment, therefore also increases population size
Economic value of the environment	Monetary value placed on a healthy estuary as well as the value proffered to businesses and the community through regional tourism	Is increased by higher real estate values and good environmental quality, however, change in the economic value of the environment does not impact any other variable
'Eco-government' decisions	Decisions that improve *Environmental quality*	Increases actions by resources management/protection agencies and is influenced by development agencies
Resource management/protection agencies	Agencies mandated and resourced to enact the required level of regulation for environmental/resource use	Monitors and manages environmental quality and is influenced by 'Eco-government' decisions, NGOs and urban development agencies
Real estate values	Value of housing, land and property for businesses	Increased by population size and environmental quality and influences the economic value of the environment
Population size	Number of people residing in the area	Influences by transport accessibility, available housing (i.e. urban development agencies) and environmental quality
Urban land use	Land used for residential, retail purposes and provision of services	Increased by population size and impacts Total resource use. Reduces agricultural and industrial land use through competition for land
Agricultural/industrial land use	Use of land for agriculture and industry	Increases Total resource use in the area
Total resource use	Overall impact of population size and urban development in the region	Reduces environmental quality and stimulates 'eco-friendly' developments
Raw development industry	Use and development of land for heavy industry such as mining	Reduces 'Eco-government' decisions through lobbying and pressure to maintain heavy industry in the region
Urban development agencies	Responsible for developing land into urban centres/housing estates	Reduces 'Eco-government' decisions and management actions by Resource management/protection agencies through political pressure for housing developments
Sustainable development industry	Encourage and implement 'eco-friendly' urbanisation	Acts to reduce Total resource use through 'eco-friendly' developments and encourages 'Eco-government' decisions
Non-government organisations	Independent groups encouraging and assessing environmental management	Monitor environmental quality and encourage remedial action by Resource management/protection agencies
Regional transport	Ease of access to the area	Increased by urbanisation (i.e. housing availability) and enables easy transport to Perth or industrial areas for employment

from *Agricultural land use* and *Industrial land use* to *Nutrients*, and the link from this agricultural variable to *Base flow/water resource* (Fig. 4) (class I, $wF_n = -0.38$). In this situation, agriculture and industry may still input nutrients into waterways and the estuary; however, these new regulations ensure there is no increase in the amount of nutrients entering the system. The same situation applied for the use of base flow by agriculture; base flow can still be used but its use cannot increase.

Stability increases to a high level following the clarification of overlapping jurisdictions, as identified during model building, to leave only one agency responsible for managing water quality. This occurs through two mechanisms. Firstly, the removal of the link from *Water quality* to the *Local planning agency* and secondly, the removal of the links between the *Local planning agency* and *Reserves/wetlands* (class I, $wF_n = -1.00$). New links in the future model are from the *Local estuarine conservation group* to *Agricultural regulation*, *Waterways management* and *Environmental management & conservation*, to help ensure management is effective by providing additional backups in case the strength of any management links declines. For instance, the extra links from *Local estuarine conservation group* are predicted to reduce the actions by *Water allocation* that negatively impact *Water quality*, such as increased *Nutrients/general pollutants* through *Drain flow*. These links are also predicted to increase action by *Agricultural regulation*, *Waterways management* and *Public water management*, allowing more effective management of impacts on the estuary.

3.2. *High level governance structure*

3.2.1. *Current models*

The weak-link high level governance model has a relatively low potential for stability (class I, $wF_n = -0.33$) and is ineffective, similar to the local governance model, because there are no management agencies or other variables that improve *Environmental quality*. The strong-links model is even

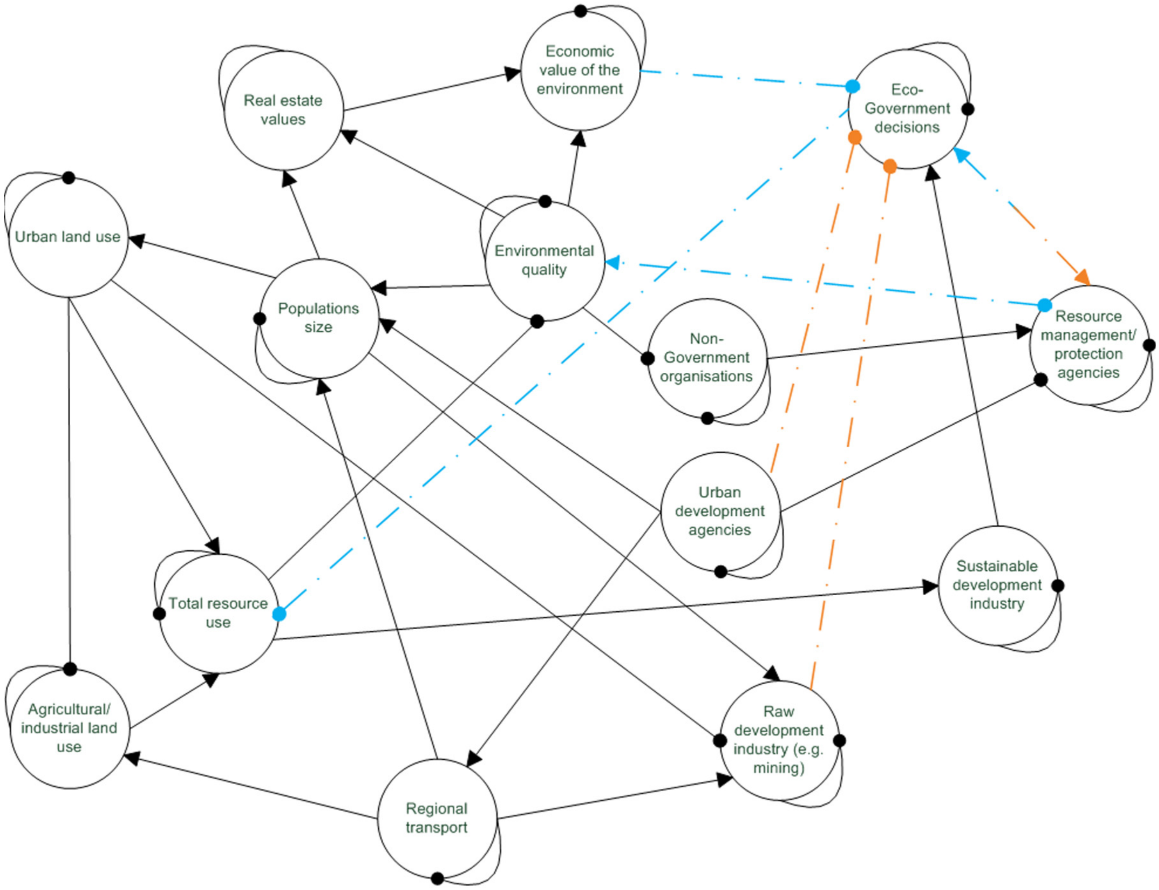

Fig. 6 – Future high-level governance model with links to be included (dashed blue lines) and links to be removed (dashed orange lines) to improve stability, management and governance.

less stable (class I, $wF_n = -0.17$) despite *Resource management/protection agencies*, the *Sustainable development industry* (*i.e.*, 'green' developments), *Eco-government decisions* and *Urban land use* all being predicted to positively impact the environment. Instability is higher in the strong-links model due to reciprocal positive links between *Resource management/protection agencies* and *Eco-Government decisions*. This feedback is problematic in that a decline in one variable will stimulate a continual decline in both variables. For example, a decline in *Resource management/protection agencies* would cause a decline in *'Eco-government' decisions*, which would, in turn, cause a further decline in *Resource management/protection agencies* and so on until neither the agencies nor environmentally-based decisions existed. This issue is addressed in the future high level governance model.

An issue in the weak-links model is the predicted decline or lack of change in *Environmental quality* following inputs to all management variables. This lack of management success is therefore addressed in the future model. *Total resource use* also plays an important role in the response of *Environmental quality* in the strong-links model. This was identified as the response of *Environmental quality* to increases in itself is ambiguous, meaning that an increase in *Environmental quality* could actually cause it to decline. This response exists due to the counteracting feedback cycles involved in the direct relationships between *Total resource use* and *Environmental quality*, and the indirect relationship between *Total resource use* and *Resource management/protection agencies* (Fig. 5). Essentially, if *Total resource use* is high, *Resource management/protection agencies* are perceived to have a minimal impact and *Environmental quality* will decline. However, if it is low, remedial actions taken by *Resource management/protection agencies* may be sufficient to improve *Environmental quality*.

An additional issue identified in the current High level governance models is the presence of ineffective feedback between *Eco-government decisions* and *Environmental quality*. An increase in *Eco-government decisions* is not predicted to have any effect on *Environmental quality* or any other variable without strong links from the government to ensure appropriate monitoring and management of the environment. In addition, in the weak-links model an increase in *Environmental quality* is predicted to increase both *Real estate values* and the *Economic value of the environment*.

3.2.2. *Future model*

Altering the high level governance model to include links that would increase environmental quality, through effective management and monitoring, resulted in a model with a high potential for stability (Fig. 6) (class I, $wF_n = -0.85$). To achieve this, negative links from the development variables (*i.e.*, Raw and Urban development agencies) to *Eco-government decisions* are removed. In addition, the links between

Environmental quality and *Resource management/protection agencies* that exist in the strong-links current model, are retained to represent strong and effective monitoring and management. As a result, action taken by *Eco-government decisions*, *Resource management/protection agencies*, *Sustainable development agencies* and NGOs are all predicted to positively impact *Environmental quality*.

The positive feedback that contributes to instability is removed through the deletion of the link from *Eco-government decisions* to *Resource management/protection agencies*. This determines that, while these agencies are still influenced by government decisions, their main role is in the management and monitoring of environmental quality regardless of any political debate.

Issues identified with the strength of *Total resource use* are diminished through the inclusion of a negative link from *Eco-government decisions* to *Total resource use* to represent new legislation for impacts from existing and new developments in the region. This relationship, if strong, can counteract the negative influence that already exists between *Total resource use* and *Environmental quality*.

In conjunction with previously mentioned changes, the negative link from the *Economic value of the environment* to *Eco-government decisions* provides the government with the opportunity to effectively improve the quality of the environment, and in doing so improve real estate values and the local economy. It is important to note that without direct effective regulations to improve or remediate environmental quality, the stimulation of additional development in the region by increased real estate values and a strong local economy is still predicted to cause environmental decline.

4. Discussion

The health of the Peel–Harvey estuary (Hale and Butcher, 2007), and many estuaries globally (*e.g.*, Glaser, 2003; Meybeck, 2003; Mallin et al., 2007), is at a critical juncture for a range of ecological as well as social and economic reasons (Rapport et al., 1998; Rogers et al., 2010). Water and environmental quality were the most important assets identified by stakeholders and are generally in poor condition with algal blooms, deoxygenation and undesirable changes to the aquatic communities commonplace. Action is necessary to circumvent further environmental decline and the discontent of local communities as a result of a return to a hyper-eutrophied state. Impacts on water and environmental quality occur throughout the catchment and qualitative modelling of the governance structure of this system highlighted that management must focus on the root cause, not simply the observed effects. In addition, gaining an understanding of key drivers and dynamics associated with the social–ecological system through processes such as stakeholder-informed qualitative modelling is important as a prerequisite for genuine action to occur.

Ostrom's (1990) eight design principles for governance mechanisms in long-lasting commons are relevant when assessing issues in systems such as that represented by the Peel–Harvey governance models. For instance, Ostrom's first two design principles were: (1) clearly defined boundaries of the commons; and (2) rules for the appropriation and provision of common resources. We can think of these principles as the requirement for departments and agencies to have a clear understanding of resource users and their rights as well as the responsibilities and public expectations for management. In the Peel–Harvey estuary, different stakeholder perceptions of the existence and strength of links was the result of unclear roles and responsibilities. Furthermore, the effectiveness of catchment-level policy interventions is frequently limited by overlapping jurisdictions and fragmented administrative structures. In some cases this resulted in weak or non-existent monitoring of assets–another key principle for the design of governance structures (Ostrom, 1990). In order to determine the most appropriate management strategies, clear lines of responsibility were incorporated into the future models. Problems with overlapping responsibilities are also apparent with the urbanisation of wetlands around the world, which are often prime waterfront real estate. Wetlands are critical habitat for wading birds, and act as a natural filter to reduce pollutants entering the estuary (EPA, 1993). Such issues are commonplace, and a sustainable approach to land and water management has proved difficult to achieve in other locations (Franks, 2010).

The need for sanctions for those that violate rules was also identified by Ostrom as a key principle that should be addressed in governance systems. In some cases, the Peel–Harvey system lacks a means of ensuring compliance with rules. For instance, agricultural and industrial inputs reduce water quality in the estuary, yet they cannot be regulated by the government department mandated to manage public water resources and there is no consistently effective strategy to deal with non-compliance. In the Philippines, irrigation systems were found to work more effectively when compliance was controlled by the farmers themselves rather than by the government (Araral, 2009). However, such situations are likely influenced by the social networks of the farmers including the widespread integration of infrastructure providers within the community of irrigators (Anderies et al., 2004). At a larger scale, such as in developing countries where foreign aid is often provided to public agencies that are not always dedicated to the swift improvement of public welfare (Araral, 2008), ineffective governance structures can result in widespread non-compliance that may take decades to recover from. While this is not the case for governance in the Peel–Harvey estuary, the transfer of compliance control to the public is also not likely to be an effective option. This is because the resource users (*i.e.*, the general public) are a disparate entity. That is, they do not know each other and are totally removed from any decision-making except through local and state elections. Similarly, in order for the rules to be complied with there is a need for legislation to support the regulator.

Many governance systems around the world could benefit from mutual accountability, either through the integration of effective approaches to management by different departments (*i.e.*, the Peel–Harvey estuary) or the confirmation that funds provided have actually resulted in effective remedial actions (Mookherjee, 1997). A lack of accountability was identified as a critical issue for the success of environmental strategies when strong environmental management and monitoring alone were found to be insufficient to improve water quality and socio-economic assets. Mutual accountability occurred in the models as feedback between the responsible agencies and departments and the environment, and is critical to ensure each aspect of the system is performing successfully. Feedback essentially allows for 'self-correction' and adaptability, and was found to be nonexistent in the weak-link local governance model and ineffective in the strong-link local governance model. The effectiveness of management improved when direct measures were incorporated into the future models to monitor and regulate the processes indirectly affecting water quality. This result showed the value of governance structures that are expanded from merely water and estuarine management to broader, more integrated frameworks (Memon et al., 2010). In Europe, a suggested reason for the inability to achieve sustainable approaches to estuarine management was a lack of accepted trade-offs between agricultural or industrial land-use, and a scarcity of land required for the preservation of water quality and the environment (Franks, 2010).

A net gain in social, economic or environmental benefits (*i.e.*, beneficial outcomes for the environment, increased real estate values, etc.) was predicted in all models following an improvement in the environment. Thus, it would appear that a transaction cost (*e.g.*, Williamson, 1981; Araral, 2013) or trade-off between the resource sector, conservation and business interests should not be a major concern in the Peel–Harvey system. Unfortunately, altering perceptions as to the holistic benefits of improving environmental health while also maintaining business and resource interests may not be easy to achieve. In addition, the adoption of new ideas or techniques for environmental management is often perceived to be difficult (Guerin, 1999) and therefore slow to gain traction. This is particularly the case if the change requires integration with existing management or if the process is difficult to understand. Effective communication may be the critical factor in driving the adoption and success of environmental strategies.

Effective communication will be valuable for the adoption of any new idea or governance strategy. Effectiveness may be dependent on whether a direct or indirect process for improvement is involved. For instance, Guerin (1999) suggested that a land-owner would be more likely to alter land-management practices when the current practice directly impacts the productivity of their land, such as grazing on contaminated land, than for indirect measures that increase productivity, such as reducing pollution on nearby farms. In addition, the adoption of new environmental strategies is dependent on the trade-off between immediate and long-term benefits. For example, it can be argued that reversing a decline in environmental quality is in the best interests of the community as it increases real estate values and benefits the local economy. However, in the relatively short political time-frames that exist today, there may be little perceived benefit in immediate expenditure to observe a benefit in five to ten years. Growing public awareness of environmental issues may combat this to some extent if environmental management is also seen as political sustainability (Levy, 1997).

Qualitative modelling proved to be a valuable technique to focus stakeholders on core variables and drivers of change for the assessment of strategies for improvement in the Peel–Harvey estuary. We suggest this technique will have similar effectiveness in guiding research and focussing management on key issues in other fields dealing with complex systems. The theory behind the technique was first implemented in economics in the mid 1960s (Quirk and Ruppert, 1965) and has also been used in fisheries management (Metcalf et al., 2010, 2011), assessment of mining impacts (Dambacher et al., 2007) and the identification of climate change and coastal governance issues (Stocker 2011). The method is relatively quick to use, in comparison to other data-intensive models, cost-efficient and easily incorporates stakeholder input. The ability to produce models during workshops is beneficial to ensure stakeholder agreement on model structure, and to identify new links and variables of importance. One limit of the approach is that the models apply to equilibrium systems (Justus, 2006); however, where thresholds for shifts between states are known, multiple alternative models can be used to represent alternative states (Marzloff et al., 2011). The inability to precisely predict the magnitude of a perturbation response is another limitation of the technique. In addition, qualitative models are limited by size and complexity. For example, a large (>20 variables) model that is also very complex (*i.e.*, variables with numerous reciprocal links) will tend to be highly ambiguous and may therefore be relatively unreliable (Dambacher et al., 2003). This limitation may be overcome by ensuring models focus on a relevant subsystem of a size and complexity that will allow high predictability while also ensuring inclusion of key variables, or through the integration with quantitative modelling techniques (Metcalf et al., 2010).

The Peel–Harvey estuary is returning to a highly eutrophied state; qualitative models suggest that, as they stand, the management structures are insufficient to halt this decline, let alone rehabilitate the system. While scientists and managers are aware of the severe ecological problems in the Peel–Harvey estuary, the critical point (here and in many other places globally) is that stakeholders and the general public lack an effective means to rehabilitate and manage the system due to ineffective governance structures, or policies that are only weakly implemented. These governance problems are seen as a common theme through the six different models elicited in this study. Alterations to governance structures are likely to be aided by the consideration of Ostrom's (1990) design principles for robust governance systems. In addition, the use of qualitative modelling to identify strategies for improved governance or management can be used broadly across different social, economic or ecological problems and locations.

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