Multiple Stable States and Thresholds Within the Goulburn Catchment

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EXTENDED ABSTRACT

Over the last decade, ecosystem management has been tending toward understanding ecosystems as having multiple stable states. Often such states are characterised as socially desirable and undesirable, with for instance high/low fish stocks or oligotrophic/eutrophic lake states. Their significance is that small stochastic forces may force the system over a threshold toward an alternative, potentially undesirable, state. Until recently no investigation of similar behaviour in regional agricultural catchments has been made. This paper further develops the only published model of a regional agricultural catchment system predicted to have such multiple states.

Simple analytical models have been developed to numerically predict the existence of such multiple stable states. They are models of physical behaviour, comprised of a set of ordinary differential equations (ODE), with each equation defining the evolution of a state variable. Bifurcations of the ODE models provide a means of identifying the set of stable states and the thresholds between them, and thus quantifying the resilience of current state of the system to shocks.

The resilience of agricultural catchments has recently begun to be qualitatively addressed. The only catchment-resilience model is a salt and water groundwater-unsaturated zone model of the Goulburn catchment (Anderies 2005). The catchment is modelled at two connected lumped regions; one for the lowland plains and the other for the uplands. It predicts the catchment to have only two stable states; one of deep water table depth and low stream salt loads and the other of a water table approaching the surface and high salt loads. It predicts that beyond 15.4% of land clearing in the upper Goulburn, the system has only the latter state. This paper expands upon this model to test these predictions.

The predicted two states are the result of a positive feedback loop emerging as the depth to the water table becomes very shallow. It results in high soil salinity which reduces transpiration, and in turn increases groundwater recharge, thus closing the feedback. Lumping of the Goulburn catchment into only two regions treats the landscape salinity processes as uniform across the catchment, rather than varying locally and realistically. This inconsistency was investigated by subdividing the upland region of the model. This tests its predictions with greater spatial resolution and more realistic representation of critical processes.

The multiple stable states predicted by the original model do not appear to be an artefact of the degree of spatial lumping. Expanding the model from two lumped regions to three and four regions still produces the predicted multiple states. Significantly more complex stability structures did emerge but the general properties of a cluster of stable states at only a deep water table and another at an approximately zero water table depth persisted. Included in these sets, and in the 2-region model, were previously unpublished stable states produced by non-uniform shocks applied across the regions.

The phenomena predicted by these models have major implications for stream and landscape salinity management. These predictions are, however, based upon a very simple and highly spatially lumped model. Future work will apply a greater spatial resolution in order to allow more rigorous calibration against stream and groundwater hydrographs, and thus more valid identification of stable states and thresholds.

If the predictions of multiple stale states for the Goulburn catchment are correct, then based upon the very high percentage of cleared land, the entire catchment should have only the shallow water table stable state. As the percentage of land cleared has significantly increased throughout the last century within the catchment, it should also have switched from having at least two stable states to the current single stable state. If this is correct, it should be observable in the catchment data. An investigation of whether it is will be undertaken following refinement of the model.

1. INTRODUCTION

Over the past decade, ecosystem management has been tending toward understanding ecosystems as having multiple stable states (Gunderson et al. 2002). Often such states are characterise as socially desirable and undesirable states, with for instance, high/low fish stocks or oligotrophic/eutrophic lake states. The significance is that small stochastic forces may force the system over a threshold toward an alternative, potentially undesirable, state. Much of the modelling undertaken in this field has focused on ecological systems. Until recently no investigation of similar behaviour in regional agricultural catchments has been made. This paper further develops the only published model of a regional agricultural catchment system predicted to have such multiple states.

The investigation of ecosystems as having multiple stable states has predominantly been driven by the Resilience Alliance (www.resalliance.org) and its publication *Ecology and Society* (www.ecologyandsociety.org). Much of the focus to date has been on the qualitative understanding of regional natural resources and their interaction with society when managed for extraction. More recently simple analytical models have been developed to numerically predict the existence of multiple stable states. These models are based on physical principles and comprise of a system ordinary differential equations (ODE), each describing the evolution of one state variable. Bifurcation of the solution to the ODEs allows estimation of the stable states and thresholds with a change in a model parameter. With respect to management, this provides an understanding of the change in number and state space location of the stable states which changes in a management option, such as percentage land cleared or fire frequency.

Bifurcation of the solution to the ODEs also allows quantification of the system's resilience. Ecological resilience, while having some variation in definition (Brock 1998; Perrings 1998), is generally context dependent. That is, it considers the magnitude of force *W* to shift resource *X* from state *Y* to state *Z*. As the change of states should be a function of the system structure, and not the historic stochastic forces exerted upon it, the states are measured from the centre of stability of the current stable state to a threshold (i.e. state space ridge) into the alternative state (Lélé 1998). Ecological resilience, unlike engineering resilience, does not focus on the duration until return to a single stable state following a perturbation or shock. Bifurcation allows the plotting of these stable states and thresholds and as such quantification of the system's resilience.

As mentioned previously, much of the numerical resilience analysis has focused on ecological systems such as lakes subject to eutrophication (Janssen et al. 1999), lake fish stocks (Carpenter et al. 2004) and rangeland grazing (Janssen et al. 2000). Analysis of agricultural catchments has recently begun to be qualitatively addressed, though with a focus on the interaction of the physical system with its management and use (Walker et al. 2002; Allison 2003; Allison et al. 2004). The only catchment-resilience model published to date is that of Anderies (2005). This model, which is a salt and water groundwater-unsaturated zone lumped model of the Goulburn catchment (Victoria, Australia), predicts it to have only two stable states. As a result of the widespread land clearing it predicts one of the stable states to have been lost and the catchment to have only one stable state remaining. This state is of near-zero depth to groundwater and very high salt export. This paper expands on Anderies (2005) to test the predictions of the Goulburn currently having only this single and undesirable stable state.

2. A REGIONAL ODE MODEL OF THE GOULBURN CATCHMENT

The Anderies (2005) model is a simple salt and water balance dynamic model of the Goulburn catchment. It models the catchment as two regions, the lowland regional plains, comprising the Shepparton Irrigation Region (SIR), and the upland region dominated by dryland grazing and cropping. Each region is characterised by three state variables and their evolution given by a set of ODE equations: $dDBNS/dt$ (DBNS: depth below natural surface of the water table); $dSoil\_Salt\_Mass/dt$; and $dGroundwater\_Salt\_Mass/dt$. Darcy's law is also used to dynamically estimate lateral groundwater flow from the uplands to lowland region. Simulations are at an annual time step.

A detailed description of the model is beyond the scope of this paper (see Anderies 2005 for detail). Below is a brief review of the model followed by the setting of the model in context with existing regional salinity models.

2.1. Model Review

The Anderies model was developed "as an alternative to the practice of using existing models [*see Table 1*], originally developed for a different set of questions at a scale not appropriate to regional agroecological and water policy issues" (Anderies 2005). Therefore this review is not a critique of the model's simple hydrological assumptions against more detailed models. Instead, some of the more significant assumptions of the model are discussed in the context of the model's purpose.

Rainfall is partitioned into evaporation, runoff, infiltration, transpiration and recharge using a set of parametric equations. Unlike other models, such as BC2C (Dawes et al. 2004), the partitioning is dependent upon, in addition to annual rainfall, the depth below natural surface (DBNS) of the water table and the soil salinity. The model does not include a state variable for soil moisture, thus assuming the annual change in soil moisture storage is negligible. This exclusion of a soil moisture store causes any infiltration uptaken by the plant to go to recharge within the year, thus ignoring the often considerable time lag of infiltration to produce recharge.

The lack of a soil moisture state variable also forces runoff to be a function only of annual rainfall. Thus, runoff is independent of DBNS and soil salinity and lumps infiltration excess and saturation excess runoff (Beven 2001).

Stream flow is the sum of surface runoff and baseflow, while non-groundwater subsurface discharge is ignored. Importantly the model dynamically simulates baseflow as a function of the DBNS, thus allowing a stream to switch between gaining and losing groundwater. Darcy's law is used to estimate the flow as a function of the head difference between the groundwater and the stream (which is assumed to be at the surface elevation). Anderies (2005) parameterised the coefficients for Darcy's law such that groundwater flows into the stream for all DBNS. A practical limitation of the model is that this parameterisation, while also very difficult to estimate, depends on the surface area of the region. This is due to the need to estimate the stream cross section area and the distance between the two head estimates. It therefore must be re-estimate when a model region is subdivided and as such should be used as a calibration parameter.

Like the non-lagged routing of infiltration to recharge, the interaction between the DBNS within a region and the baseflow is also non-lagged. That is, if the watertable becomes shallower within a time step, the baseflow will also increase. This is due to the model's inability to simulate differing DBNS within a region. While this assumption is less significant within the local and intermediate groundwater flow systems of the upland region, it is not realistic within the regional groundwater flow system of the lowlands region. The very low hydraulic gradients of the lowlands ensure that the lag time between a local change in DBNS and a change in baseflow is orders greater than one year.

Anderies (2005) reports that bifurcation of the model for the percentage of land cleared within one region, when the other region is not cleared and not irrigated, produces two stable states. The first has a deep DBNS, high soil salt store and the second a near zero DBNS, low soil and groundwater salt store. As the percentage of land cleared within the upland region approaches 15.4%, the resilience within both regions falls dramatically such that only very minor shocks (i.e. above average rainfall or widespread but small changes in landuse) will push the system over the threshold and into the undesirable state of near zero DBNS. When the percentage cleared exceeds 15.4%, only the near zero DBNS state exists. The current percentage of the catchment cleared is approximately 65% in uplands and 90% in the lowlands (Goulburn Broken Catchment Management Authority 2002). According to the model the catchment is tending toward a state of zero DBNS, resulting in a significant and long-term increase in the region's salt exports.

The multiple stable states emerge from a change in rainfall partitioning. As the water table becomes shallower, both infiltration excess runoff and capillary discharge increase. As the soil profile becomes more saline, the vegetation's maximum transpiration and transpiration efficiency (percentage of the infiltration that is transpired) also decline, resulting in decreased transpiration and increased recharge. This initiates a positive feedback cycle of shallow DBNS and high soil salt store reducing transpiration, which increases recharge and causes the DBNS to fall further and therefore the transpiration to fall again.

While the model does have numerous sources of parametric uncertainty, potential structural uncertainties may invalidate the prediction that multiple stable states exist. A region suffering from landscape salinity rarely, if ever, has a near uniform DBNS over its extent. Mainly due to topography, the water table is shallow at very limited sites, such as alluvial depressions and breaks of slope (Coram 1998). This is clearly displayed within the Salinity Management Plans for the region (Salinity Pilot Program Advisory Council 1989). Therefore while such sites, according to the model, will have crossed the threshold into the shallow DBNS state, in practice the vast majority of a region will not have crossed this threshold and will remain in a deeper DBNS state. The critical percentage of land cleared, above which only the shallow DBNS state exists, may therefore also be significantly higher. This paper investigates this factor by modifying the Anderies (2005) model within Simulink® in order to increase its spatial detail within the upland region and simulate more realistic representation of processes critical to its predictions.

2.2. The Model in Context

The Anderies (2005) model, and the variants presented herein, are significantly different from existing Australian regional salinity models, with respect to both purpose and structure. Table 1 is an incomplete list of regional salinity management models (Beverly 2002). As bifurcation of the Anderies (2005) model considers water balance changes as a result of deforestation, two models focusing only on stream flow changes as a result of landuse change are also included.

The models in Table 1, with the exception of CAT Salt (Vaze et al. 2004) and Anderies (2005), do not dynamically model recharge, requiring an a priori estimate to be supplied. Anderies (2005) is also the only model to be based explicitly on a set of ODEs, thus allowing bifurcation.

Table 1. Expansion of Anderies (2005) model within Simulink® to model three regions. ODE: Ordinary differential equations. PDE: Partial differential equations.

Model	Spatially Distributed?	Deterministic (D) / Parametric (P)	Solute Transport	Dynamic Modelling of Physical Processes: Infiltration	Dynamic Modelling of Physical Processes: Groundwater	Dynamic Modelling of Physical Processes: Surface water	Model Structure (ODE, PDE, 'Buckets')
ModFlow Regional Groundwater model	✓	D	✗	✗	✓	✗	PDE
Flow Tube	~✓	D	✗	✗	~✓	✗	PDE
CAT Salt	✓	D	✓	✓	✓	~✓	PDE
CRC CH 2cSalt	✓	D	✓	✗	✗	✓	Buckets
BC2C	✓	P	✗	✗	✗	✓	n/a
CRC CH FCFC	✗	P	✗	✗	✗	✓	n/a
Anderies 2005	✗	D&P	✓	✓	✓	~✓	ODE

3. METHODOLOGY

To investigate the sensitivity of the predictions from the Anderies (2005) model to greater spatial detail, the model was implemented within Simulink®. This allowed simple expansion to any number of regions as two Simulink library blocks were defined (a generic region and lateral groundwater flow between regions) and can be linked to simulate any number of regions.

Bifurcation was undertaken numerically within MatLab® using a Broyden Updating Newton-chord pseudo-arc length predictor corrector algorithm (Kuznetsov 1995). This algorithm traces a line of zero state-variable derivatives as a function of the change in a model parameter, in this case the percentage area of cleared land in the upland region. To ensure all zero-derivative states are traced, a local minimisation/maximization recursive algorithm was developed. Starting from a very deep DBNS, the algorithm perturbed the DBNS of each region until a new stable state was located. Bisection was then used to locate the unstable threshold between the two stable states. The algorithm then called itself in order to locate other stable states from this new stable state. This algorithm ensured all stable states were identified.

In testing the predictions of Anderies (2005), the original model was changed minimally to ensure a valid comparison. The inclusion of additional model regions therefore preserved all of the parameterisation of Anderies (2005). That is, for the three-region model the upland region was sub-divided into two regions (Table 2) and i) the drain conductance was scaled to ensure an equal base flow discharge per km^2 as Anderies (2005) and ii) Darcy's Law parameters were scaled to ensure an equal lateral flow into the lowlands region. The only exception to this was the drain conductance within the second lowest elevation region (region 2). It was increased to 5000 m/year in order to produce plausibly deep DBNS for zero land clearing. Also, the fraction of land clearing at each point of the bifurcation was applied to all subdivisions of the upland unit, thus ensuring the same land use as in the original model.

Table 2. Summary parameter values for Anderies (2005) and the extended models.

Model	Sub-Region	Area (km^2)	Elevation (mAHD)
Anderies 2005	1	5,000	100
	2	5,000	700
3 Region	1	5,000	100
	2	2,500	200
	3	2,500	550
4 Region	1	5,000	100
	2	2,500	200
	3	1,250	400
	4	1,250	550

4. RESULTS AND DISCUSSION

4.1. 2-Region Model Revised

Figure 1 shows the DBNS bifurcation results for the lowlands and uplands of the two-region model.

For a set fraction of land clearing in the uplands, the plots give the very long term evolution of system from initial conditions. As the fraction of land clearing changes, the attractor (i.e. stable states) to which the system evolves also changes. Beyond 15.4% clearing the DBNS within region 2 is predicted to evolve towards zero. Corresponding to such a shallow DBNS are very low soil and groundwater salt stores. This is only due to a very long period of high stream salt loads in which the stores are discharging.

In all of the figures below, the attractor and repeller (unstable threshold) curve approximating a ‘>’ is due to the reduction in transpiration from an increased soil salinity and shallower DBNS. The approximately horizontal attractors and repellers greater than zero are additional states not reported in Anderies (2005). These are due to a shock being exerted only on a neighbouring region, causing it to approach the near-zero-DBNS attractor. The change in lateral flow produces, in the case of the lowland region, a new stable state at approximately 12.5 metres DBNS. Importantly, these newly identified states occur only when the shocks are not uniformly applied to all regions. Also, unlike Anderies (2005), new attractors within the lowland region are still present up to 100% land clearing.

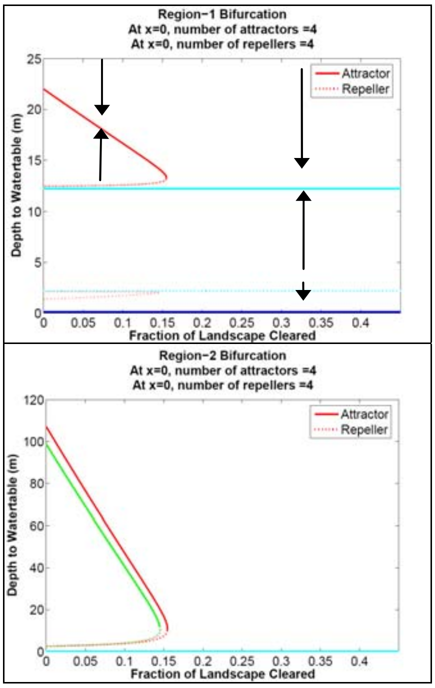

Figure 1. 2-Region DBNS bifurcation. Lines of equal colour across the set of plots correspond to the same stability/threshold state.

4.2. 3 & 4-Region Models

In Figures 2 and 3 are the DBNS bifurcation results following subdivision of the upland region of the Anderies model into 2 and 3 sub-regions respectively. Most significant is that for all regions of both models, like the two-region model, only two sets of attractors exist. Below a critical fraction of land clearing, all models have a set of attractors clustered at a deep DBNS and a second set at a very shallow DBNS, with no continuum between. The only slight exception is an attractor in the most downstream region, at a deep DBNS independent of the fraction of clearing.

The most significant difference arising from the increased spatial resolution of the 3- and 4-region models is the more complex set of attractors at a deeper DBNS. These are a consequence of combinations of adjacent regions approaching the near zero DBNS attractor set. The second major difference is the fraction of clearing beyond which only the zero DBNS attractor set exists. For the 3-region model, the central region’s critical fraction of clearing is increased from 15.8% to 26%. For the 4-region model, the critical fraction of land clearing in regions 2 and 4 is also increased, to 24% and 43% respectively. While this critical fraction is sensitive to the stream discharge coefficient (see Section 2), the parameter values used in the 3- and 4-region models were scaled to preserve the discharge of the original 2-region model. The increased spatial resolution of the model may therefore highlight the very generalised concept of a smaller fraction of cleared land being required to put the downstream end of a catchment more at risk of shallow water tables than a more upland region.

5. CONCLUSIONS

The multiple stable states predicted for the Goulburn catchment by Anderies (2005) do not appear to be an artefact of the degree of spatial lumping. Expanding the model from two lumped regions to three and four still produced the predicted multiple stable states. Significantly more complex stability structures emerged with the increased spatial resolution, but the general feature of a cluster of stable states at only a deep water table and another at a much shallower water table persisted. Included in these sets and the 2-region model were newly identified stable states produced by non-uniform shocks applied to each region.

The phenomena predicted by the set of models have major implications for stream and landscape salinity management as well as water resource planning. These predictions are, though, based upon a very simple and highly spatially lumped model. The emergence of multiple states is dependent on the model parameter values, most significantly the drainage conductance and basement elevation unconfined aquifer parameters.

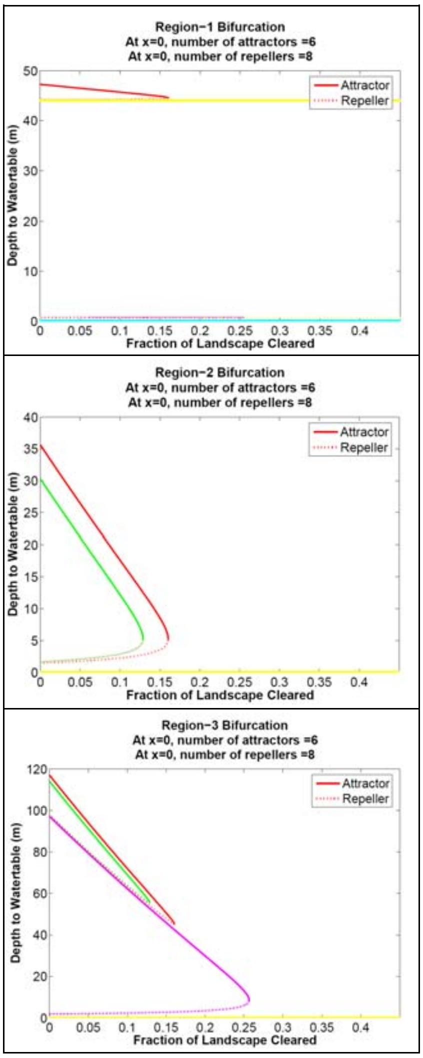

Figure 2. 3-Region DBNS bifurcation. Lines of equal colour across the set of plots correspond to the same stability/threshold state.

Future work will apply the model at a greater spatial resolution, to allow more rigorous calibration against stream and groundwater hydrographs, and thus more valid identification of stable states and thresholds.

Finally, if the predictions of multiple stable states for the Goulburn are correct then, as the percentage of land clearing within the catchment is very high, the entire Goulburn should have only one stable state, a shallow water table state, and be slowly evolving toward it. Additionally, as the percentage of land clearing rose significantly throughout the last century, the Goulburn should have switched from having at least two stable states to the current single shallow-water table state. If all of this is correct, it should be observable in the catchment data. A check of this will be undertaken following the above refinement of the model.

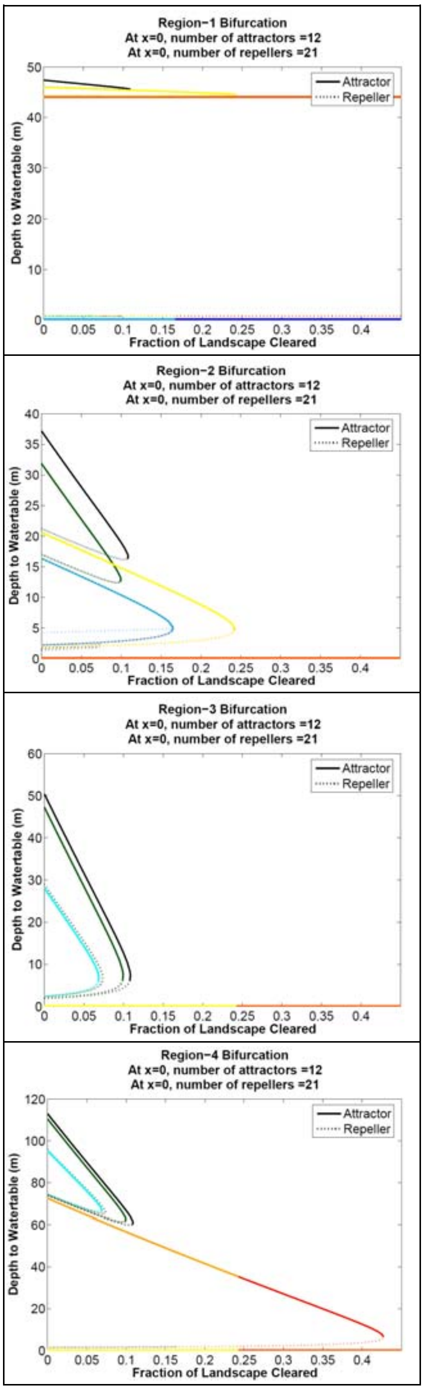

Figure 3. 4-Region DBNS bifurcation. Lines of equal colour across the set of plots correspond to the same stability / threshold state.

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