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T. J. Peterson

R. M. Argent

F. H. S. Chiew

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Validation of Multiple Stable States and Thresholds within a Saline Catchment

T. J. Peterson[1], R. M. Argent[1] and F. H. S. Chiew[2]

[1]Department of Civil and Environmental Engineering, The University of Melbourne, Melbourne, VIC 3011, Australia, E-Mail: t.peterson@civenv.unimelb.edu.au

[2]CSIRO Land and Water, Canberra, ACT 2601, Australia

Abstract: Over the last decade, many ecosystems have begun to be understood as having multiple coexistent stable states. Often such states are characterized as socially desirable and undesirable, with for instance high/low fish stocks or oligotrophic / eutrophic lake states. Within catchment planning modeling, a frequent assumption is that the equilibrium state would not change with state variable initial conditions. That is, different initial conditions will not cause a shift to a different equilibrium point, thus implicitly assuming only one stable state. Until recently no investigation of regional agricultural catchments as having multiple stable states has been published.

Simple analytical models have been developed to numerically predict the existence of such multiple stable states. Termed resilience models, they are exclusively based upon coupled differential equations, thus allowing identification of stable states and their thresholds. They do not provide improved predictive accuracy but rather the contemplation and identification of dimly perceived possible system wide changes.

The only existing catchment-resilience model is a salt and water groundwater-unsaturated zone, two region lumped model of the Goulburn catchment in Victoria, Australia [Anderies 2005]. Its minimal numerical validation and most invalidating assumption of a within-region homogenous depth to water table is discussed. Both are addressed with an expansion to it to a semi-distributed model. This was implemented for a sub-catchment of the original model in order to facilitate a more robust validation. Calibration to 29 year yield and stream salt load records is to be undertaken with consideration of equifinality. The significant prediction of saline catchments as having multiple states is thus to be validated for the first time with any rigor. Its utility to catchment planning is in encouraging a departure from assuming catchments have a single equilibrium state and thus dramatically expanding the decision space.

***Keywords**:* Goulburn catchment; Salinity; Bifurcation; Multiple States; Resilience.

1. INTRODUCTION

Recently, simple models have been developed to numerically predict the existence of multiple stable states. They 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.

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 [Allison 2003, Allison et al. 2004, Walker et al. 2002]. The only catchment-resilience model published to date is that of Anderies [2005]. This model, which is an annual timestep salt and water groundwater-unsaturated zone lumped model of the Goulburn catchment (Victoria, Australia), predicts it to have two coexistent 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 the state of near-zero depth to groundwater and very high load export remaining.

This paper addresses the most invalidating assumption of the prediction of multiple coexistent states. An expansion to the model is presented and along with a method for validation against observed data. Its purpose is not to improve the predictive accuracy of the Anderies [2005] model but rather to rigorously support a hypothesis contrary to the often implicit assumption of catchments having a single equilibrium.

Its significance to the session considering '*developing appropriate tools for environmental management and policy*' is in presenting a means for dramatically expanding the decision space of problem construction and highlighting the potential for multiple states.

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, Victoria, Australia. 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 characterized by three state variables and their evolution given by a set of ODEs: $d\,DBNS / d\,t$; $d\,Soil\_Salt\_Mass / d\,t$; and $d\,Groundwater\_Salt\_Mass / d\,t$ (DBNS: depth below natural surface of the water table). Darcy's law is also used to dynamically estimate lateral groundwater flow from the uplands to lowland region. Simulations are also at an annual time step.

Below is a brief review of the model. A detailed description of the model is beyond the scope of this paper (see Anderies 2005 for detail).

2.1 Model Review

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 parametric models, such as Zhang et al. [1999], 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 causes any infiltration not uptaken by the plant to go to recharge within the year, thus ignoring the often considerable time lag of infiltration to recharge. It also forces runoff to be a function only of annual rainfall. Thus, runoff is independent of DBNS and soil salinity and lumps infiltration and saturation excess runoff.

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 immediately increase. This is due to the model's inability to simulate differing DBNS within a region.

One of the future challenges of Integrated Assessment Modeling (IAM) is "*how to identify and represent thresholds where systems may flip from one state to an entirely different discontinuous state*" [Parker et al. 2002]. While Anderies [2005] is not strictly an integrated assessment model it explicitly addresses this challenge and thus produces a much expanded decision space. It may appear though to be a natively simple speculative model able to produce only the broadest of predictions. While partially true, prudent decision making does require that a variety of plausible hypotheses about the responses to our actions are considered, even if only dimly perceived [Ludwig et al. 1997].

2.1 Previous Results

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 and groundwater 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 disturbances (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. Currently 65% in uplands and 90% in the lowlands is cleared [Goulburn Broken Catchment Management Authority 2002]. According to the model the catchment is thus tending toward a state of zero DBNS, resulting in a significant and long-term increase in the region's salt exports.

The two region Anderies [2005] model was recently subdivided to simulate the uplands region as two and three smaller regions [Peterson et al. 2005]. In Figure 1 are the DBNS bifurcation results from the three region (two upland regions) model. For a set fraction of land clearing in the uplands, presents the equilibrium state under average climate conditions and differing initial water table states. As the fraction of land clearing changes, the attractor (i.e. stable states) to which the system tends also changes. As for the two region model, beyond 15.4% clearing the DBNS within regions 1 (lowlands) and 2 (midlands) is predicted to evolve towards zero. This expansion of the model investigated the significance of a less uniform DBNS on the prediction of multiple stable from the original model. The bifurcation of both the 3 and 4 regions did still produce a very comparable, though more complex, set of coexistent states.

2.2 Feedbacks Causing States

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 maximum transpiration and transpiration efficiency (percentage of the infiltration that is transpired) also decline, resulting in 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 rise further and therefore the transpiration to again decline.

Numerous other stable states are likely to exist in addition to that within the Anderies [2005] model. At a sub-annual time step multiple states of soil moisture have already been identified [Grayson et al. 1997]. Climate-landuse positive feedbacks have also been identified as causing a state change in precipitation following regional land clearing [Charney et al. 1974]. While only the landuse-climate multiple states are due to changes in feedbacks, as opposed to changes only in external forcing, this highlights that numerous other stable states to those within Anderies [2005] possibly exist for the Goulburn catchment.

2.3 The Model in Context

The Anderies [2005] model, and the variants presented below, are significantly different from existing Australian regional salinity models with respect to both purpose and structure. Table 1 is an incomplete list of regional Australian salinity management models [Beverly 2002].

The models in Table 1, with the exception of CAT Salt [Vaze et al. 2004] and Anderies [2005], do not dynamically model recharge, but require an a priori estimate. Only Anderies [2005] is also based on a set of ODEs, thus allowing bifurcation.

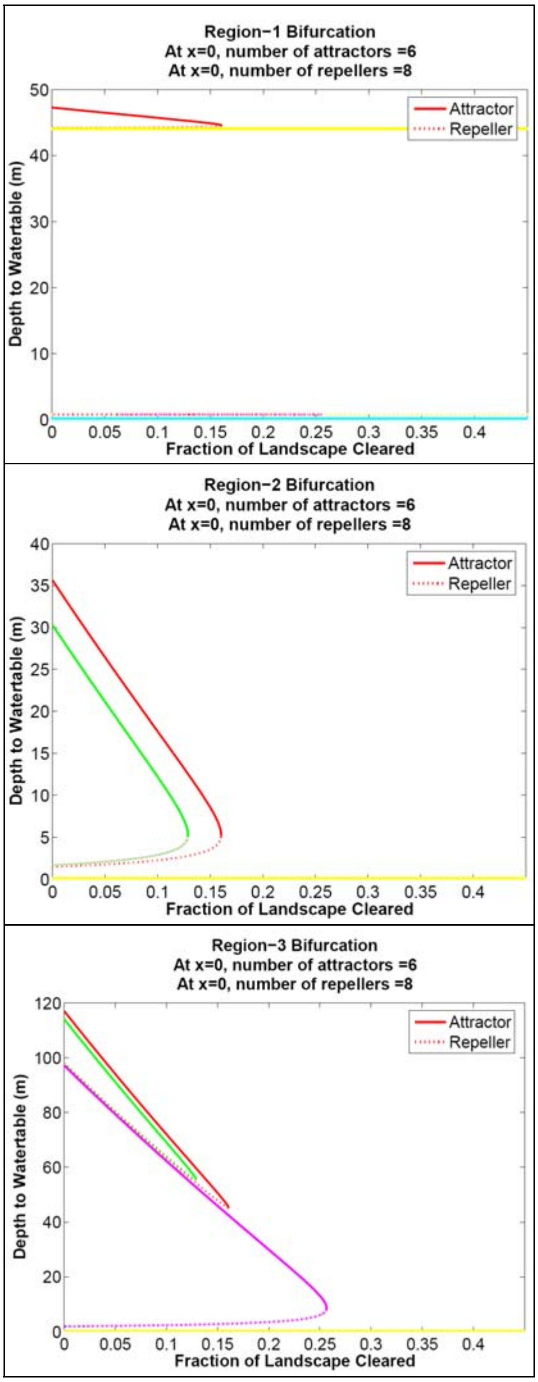

Figure 1. 3-Region DBNS bifurcation. Lines of equal color across the set of plots correspond to the same stability / threshold state. Only for the red set of lines is the water table deep in all regions.

Australian catchment hydrology models, with the exception of Anderies [2005], focus predominantly on predictions over shorter time periods, approximately sub-decades. Just as notable these models have exceptionally little emphasis on modeling positive feedbacks. This implicit bounding of catchment modeling to shorter term predictions is a likely contributor to the disregard of positive feedbacks. That is, positive feedbacks which are currently either constrained by negative feedbacks or are very slow processes are assumed constant over the short model prediction timeframe. Additionally, the current focus upon prediction over questioning our understanding of processes may also have discouraged the consideration of feedbacks and thresholds. Unfortunately these postulations cannot be referenced because of the lack of literature on the nature of catchment modeling.

Table 1. Comparison of the Anderies [2005] model with other Australian regional catchment models. ODE: Ordinary differential equations. PDE: Partial differential equations.

Model	Spatially Distributed?	Deterministic (D) / Parametric (P)	Solute Transport	Dynamic Modeling of Physical Processes			Model Structure (ODE, PDE, 'Buckets')
				Infiltration	Groundwater	Surface water	
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. SIGNIFICANCE AND VALIDITY Of COEXISTANT STATES TO PLANNING

Policy-makers and the public, it has been said [Beck 2005], are more interested in the possibility of non-linear dislocations and surprises in the environment than in smooth extrapolations of current trends [Brooks 1986]. The alternative stable states of the system dictate if and how such a system may dramatically change, while the thresholds dictate how vulnerable we are to such a change. Once crossed, the functional processes of the system have changed making recovery hysteric or irreversible.

A shift from one stable state domain to another occurs because of a disturbing force. An understanding of the stability landscape, i.e. the stable states and thresholds, provides a measure of the resilience to the cumulative impact of disturbances. Resilience modeling thus provides management with a means to assess the vulnerability to unknown future disturbances and the impact of management initiatives in expanding or contracting the current domain of stability.

3.1 Why bother with increased complexity?

The ODE model, especially when semi-distributed, is significantly more complex than a simple rainfall runoff model and dramatically more so than an annual runoff model. Conversely, it is very simple hydrogeological, omitting such processes as time varying flow directions and multiple layers. The obvious question then is why bother with this ODE model? Why not use existing models for estimation of stable states, thresholds and thus resilience.

Firstly, the simulation of thresholds and stable states requires the inclusion of positive feedbacks. As outlined in Table 1 this is omitted from most existing models, including lumped rainfall models such and ModFlow groundwater model.

Secondly, the simple addition of feedbacks to such models would still be insufficient. Only ODE models can be analyzed to detect thresholds as they require identification of the state space location of points of zero derivative and negative second derivative.

3.2 Validity of predicted coexistent states

While the Anderies [2005] 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 homogenous DBNS. Due mainly to topography, the water table is shallow at very limited sites, predominantly at alluvial depressions and breaks of slope. 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. Because of the dependency of the positive feedback processes in producing the shallow stable state, this assumption of uniform DBNS is a major invalidating of the lumped Anderies [2005] model.

To date, both the Anderies [2005] model, and other resilience models have undergone very minimal validation against observed data.

Validation of the predicted coexistent states is thus further compromised.

4. METHODOLOGY

Validating the Anderies [2005] resilience model involved expansion of it to semi-distributed structure followed by implementation to a smaller catchment and validation against observed data. Below are details of the methodology:

1. A distributed model was implemented by defining the dynamics of each region as a C# class. Creating an instance of this class for each grid cell of the catchment and fixing the flow paths allowed the development of a spatial resilience model. The ODEs were solved using the Cash-Karp adaptive step size version of Runge-Kutta;

2. To simplify validation implemented was for the significantly smaller regions (609 km^2 compared to the 10,000 km^2 of the original models) of Sugar loaf creek within the South West Goulburn. The only landuses are dryland grazing and native vegetation. Thus irrigation is thus omitted from the model and further simplified;

3. State variable initial conditions were derived from steady state values under pre-clearing landuse;

4. Validation is to be undertaken against observed stream flow and yield. Calibration will be undertaken via random sampling from the parameter space and outputs assessed against the Nash-Sutcliff Efficiency (NSE). Essentially this considers equifinality in the validation of the model. This also provides a means of sensitivity analysis through plots of the NSE against the parameter value;

5. Attractors and threshold will be numerically identified for each parameter set achieving an acceptable NSE. The state space distance between the deep DBNS attractor and the threshold will provide a spatial measure of the resilience.

5. PRELIMINARY RESULTS AND DICUSSION

To date, the above methodology has not been completed. The model structure and the ODE solver have been developed for the distributed model. This has been implemented for the Sugerloaf catchment at a grid cell resolution of 4 km^2, resulting in 459 coupled differential equations. Validation has not yet been completed, but is being undertaken to 29 years of yield and salt load stream data (gauge number 405240).

Preliminary trials from the validation suggest the following. Further work will be presented at the conference:

- Outputs are sensitive to only four parameters (stream bed saturated conductivity; two of the ten rainfall/salt partitioning parameters; and saturated horizontal hydraulic conductivity);

- Calibration, at an annual step, to the 29 year observed data can be achieved;

- Bifurcation of the distributed model produces estimates of resilience that are somewhat counter-intuitive. That is, resilience is not low only within lower relief regions such as drainage lines;

- The multiple states of the land surface are producing irreversible state changes in the catchment outputs, that is yield and salt loads.

The generality of the methods discussed throughout are two fold. The invalidation of a single equilibrium within a saline catchment can be generalized conceptually by initiating a process of questioning the assumed single equilibrium within existing catchment models. Technically, its adoption requires the inclusion of positive feedbacks within models and threshold identification requires formulation of problems as ODEs. Of these the difficulty in identifying feedbacks that may not have been previously observed appears the most challenging.

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7. REFERENCES

Allison, H. E., *Linked social-ecological systems: a case study of the resilience of the western Australian agricultural region*, PhD, Murdoch University, Perth, Western Australia, 2003

Allison, H. E. and Hobbs, R. J., Resilience, Adaptive Capacity, and the “Lock-in Trap” of the Western Australian Agricultural Region, *Ecology and Society*, 9 (1), 3. [online]

http://www.ecologyandsociety.org/vol9/iss1/art3/, 2004.

Anderies, J. M., Minimal models and agroecological policy at the regional scale: An application to salinity problems in southeastern Australia, *Regional Environmental Change*, 5 (1), 1-17, 2005.

Beck, M. B., Environmental foresight and structural change, *Environmental Modelling & Software*, 20 (6), 651-670, 2005.

Beverly, C., *A review of hydologic models for salinity management*, Cooperative Research Centre for Plant Based Management of Dryland Salinity, 2002.

Brooks, H., *The typology of surprises in technologies, institutions, and development*, W. C. Clark and R. E. Munn, Sustainable Development of the Biosphere, Cambridge University Press, p325-348, Cambridge, 1986.

Carpenter, S. R. and Brock, W. A., Spatial complexity, resilience and policy diversity: fishing on lake-rich landscapes, *Ecology and Society*, 9 (1), 8. [online] http://www.ecologyandsociety.org/vol9/iss1/art8/, 2004.

Charney, J. and Stone, P. H., Drought in the Sahara - A biogeophysical feedback mechanism, *Science*, 187 (4175), 434-435, 1974.

Goulburn Broken Catchment Management Authority, *Goulburn Broken Dryland Salinity Management Plan -Second Generation Salinity Management Plan*, Goulburn Broken Catchment Management Authority, Shepparton, Victoria, Australia, 2002.

Grayson, R. B., Western, A. W., Chiew, F. H. S. and Bloschl, G., Preferred states in spatial soil moisture patterns: Local and nonlocal controls, *Water Resources Research*, 33 (12), 2897-2908, 1997.

Janssen, M. A. and Carpenter, S. R., Managing the Resilience of Lakes: A Multi-agent Modeling Approach, *Conservation Ecology*, 3 (2), 15. [online] http://www.consecol.org/vol3/iss2/art15/, 1999.

Janssen, M. A., Walker, B. H., Langridge, J. and Abel, N., An adaptive agent model for analysing co-evolution of management and policies in a complex rangeland system, *Ecological Modelling*, 131 (2-3), 249-268, 2000.

Ludwig, D., Walker, B. and Holling, C. S., Sustainability, Stability, and Resilience, *Conservation Ecology*, 1 (1), 7. [online] http://www.consecol.org/vol1/iss1/art7/, 1997.

Parker, P., Letcher, R., Jakeman, A., Beck, M. B., Harris, G., Argent, R. M., Hare, M., Pahl-Wostl, C., Voinov, A., Janssen, M., Sullivan, P., Scoccimarro, M., Friend, A., Sonnenshein, M., BAker, D., Matejicek, L., Odulaja, D., Deadman, P., Lim, K., Larocque, G., Tarikhi, P., Fletcher, C., Put, A., Maxwell, T., Charles, A., Breeze, H., Nakatani, N., Mudgal, S., Naito, W., Osidele, O., Eriksson, I., Kautsky, U., Kautsky, E., Naeslund, B., Kumblad, L., Park, R., Maltagliati, S., Girardin, P., Rizzoli, A., Mauriello, D., Hoch, R., Pelletier, D., Reilly, J., Olafsdottir, R. and Bin, S., Progress in integrated assessment and modelling, *Environmental Modelling & Software*, 17 (3), 209-217, 2002.

Peterson, T. J., Argent, R. M. and Chiew, F. H. S., *Multiple Stable States and Thresholds Within the Goulburn Catchment*, A. Zerger and R. M. Argent, MODSIM 2005 International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand, 2005.

Salinity Pilot Program Advisory Council, *Goulburn Dryland Salinity Management Plan*, Salt Action, Victoria, Shepparton, Victoria, Australia, 1989.

Vaze, J., Barnett, P., Beale, G., Dawes, W., Evans, R., Tuteja, N. K., Murphy, B., Geeves, G. and Miller, M., Modelling the effects of land-use change on water and salt delivery from a catchment affected by dryland salinity in south-east Australia, *Hydrological Processes*, 18 (9), 1613-1637, 2004.

Walker, B., Carpenter, S., Anderies, J., Abel, N., Cumming, G., Janssen, M., Lebel, L., Norberg, J., Peterson, G. D. and Pritchard, R., Resilience management in social-ecological systems: a working hypothesis for a participatory approach, *Conservation Ecology*, 6 (1), 14. [online] http://www.consecol.org/vol6/iss1/art14/, 2002.

Zhang, L., Dawes, W. R. and Walker, G. R., *Predicting the effect of vegetation changes on catchment average water balance*, Cooperative Research Centre for Catchment Hydrology, Technical Report 99/12, 1999.