DRYLAND SALINITY MANAGEMENT: PROSPECTS FOR HYDROGEOLOGICAL AND ECONOMIC MODELLING

J. Gomboso, F. Ghassemi, and A. Jakeman.
Centre for Resource and Environmental Studies,
Australian National University[1]

Paper Presented to:

AUSTRALIAN AGRICULTURAL ECONOMICS SOCIETY
36th Annual Conference
University of Sydney, New South Wales, 9-11 February 1993

ABSTRACT:

By incorporating economic simulation techniques into a hydrogeological modelling framework, an assessment of the current and future impacts of varying a catchment's landuse patterns on groundwater levels and agricultural output can be made. The choice of alternative land use patterns that should be adopted to improve farm income in an area affected by dryland salinity, will depend upon the effects of various crop, pasture and tree species on dynamic and spatial groundwater fluctuations; and on the relative returns of those species.

This modelling framework is being applied to the North Stirling Land Conservation District, a severely salt affected area located in south-west Western Australia.

---

[1] This research has been supported by a postgraduate research scholarship from the Rural Industries Research and Development Corporation, Canberra, and the Centre for Resource and Environmental Studies, Australian National University.

1. Introduction and Study Area

Mathematical models of groundwater flow are beneficial tools for the management of agricultural systems affected by dryland salinity. Basically, if the required data (water use by different crops and pastures under various climate and soil physical conditions) are available, they can be used to gauge the spatial and temporal effects of land-use on recharge, discharge, groundwater levels and saltflow. Furthermore, by incorporating an economic component into the simulation, the estimated effects of those land-use practices on both the current and future value of agricultural production may be derived.

This methodology is currently being applied to a land conservation district in Western Australia. The North Stirling Land Conservation District (NSLCD) is located north of the Stirling Range National Park, Western Australia. The District extends approximately 50 km east-west and 20 km north-south, encompassing an area of about 100,000 ha. The flatter country to the north of the Stirling Range is underlain by sediments and characterised by poor drainage, resulting in the formation of numerous salt lakes. Average elevation throughout the flatter areas of the District is approximately 240 m above sea level *(Lennard & Nulsen, 1985)*. Rainfall occurs mainly between the months of April and October and decreases from an average of about 510 mm per annum in the south-west to 490 mm in the east.

Clearing of land for agriculture occurred between the late 1950's and early 1970's. The District is made up of approximately 80 farms which range in size from 200 to 10,000 ha. The main crop and pasture types grown on the NSLCD include: wheat, barley, oats, lupins, medic-based pastures and phalaris. The rise in groundwater levels following clearing and the use of low water-using crops and pastures, has caused dramatic secondary salinisation over a short period of time *(Western Australian Department of Agriculture, 1988)*.

The groundwater level has risen by up to 12 m since clearing and is less than 3 m from the soil surface throughout most of the study area *(Lennard & Nulsen, 1985)*. In some areas, groundwater has risen within 1 m of the ground surface, resulting in extensive land salinisation *(Appleyard, 1989)*. The salinity of the groundwater increases with depth, and ranges from 5,000 - 10,000 mgL^{-1} Total Dissolved Solids (TDS) at the top of the aquifer to 90,000 - 177,000 mgL^{-1} TDS at its base.

2. Hydrogeological Modelling

The NSLCD aquifer has been simulated for steady state and transient groundwater flow using a finite-difference approximation of the two-dimensional partial differential equation for horizontal groundwater flow *(Gomboso & Ghassemi, 1992)*. The area being simulated is located in the south-east part of the NSLCD. This area extends 28 km east-west and 7 - 14 km north-south, encompassing an area of approximately 26,000 ha. (Refer Figure 1). This area was further subdivided into a 29 x 13 array, by superimposing a 1,000 m square grid on the study site. Due to the geometry of the simulated area, only 248 nodes out of a possible 377 were within the model boundaries.

Geological, hydrological and climate data was used to estimate the initial input data necessary for the calibration of the steady-state and transient models The steady state model was calibrated using 25 March 1988 data, where the rainfall was very low and the groundwater levels were almost static *(Gomboso & Ghassemi, 1992)*. Appropriate parameters and boundary conditions were determined to yield a close agreement between the modelled and measured groundwater levels (Figure 1)

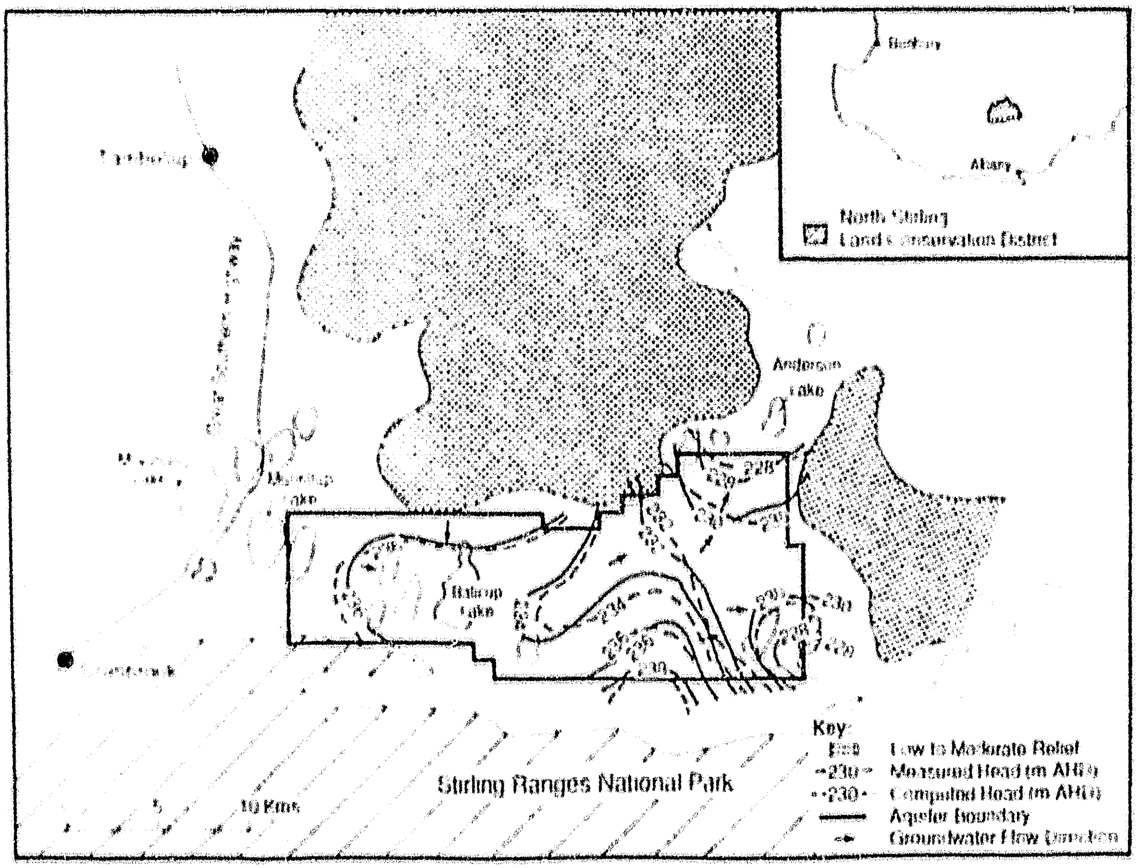

Fig 1 Location map of the North Stirling Land Conservation District (Appleyard 1989) and measured and computed piezometric head (in m AHD) of the NSLCD aquifer in steady state

The period of 24 July 1986 to 9 January 1989 provided the data for the calibration of the transient model of groundwater flow for the NSLCD aquifer. In the calibration procedure for the transient model, transmissivity values and boundary conditions for the NSLCD aquifer similar to those derived for the steady-state model have been used as a guide for optimising the fit between modelled and measure groundwater levels. However, due to limited data available on the proportion of rainfall contributing to recharge, and the water use under different land use practices, as well as the vertical discharge of the shallow aquifer via evaporation, separate models are being developed.

Once these estimates have been incorporated into the transient model, both the spatial and dynamic variation in groundwater levels across the catchment can be simulated, and estimates of the groundwater balance components for each time-step can be determined. Furthermore, by extending the calibrated transient model to forecast the dynamic effects of current land-use options on the hydrodynamic behaviour of the catchment, comparisons may be made between the current period and long-run effects of alternative land-use options.

3. Combining Hydrogeology with Economics

Although the calibration of steady state and transient models will be beneficial for documenting the extent of the physical problems caused by rising groundwater levels under various land uses throughout the NSLCD, these models do not provide a satisfactory decision-making framework for the *allocation of resources*. Economics can contribute to the resolution of natural resource conflicts, by concentrating specifically on the allocation of scarce resources among competing demands (*Morris et al, 1988*).

"*From an economic standpoint, the central objective of natural resource management should be to obtain the highest value to society, over time, from the use (including conservation) of resources. ... The objective is thus not necessarily to minimise land degradation, or to preserve certain species or areas of land, or to attain some other physical or technical target; it is to ensure that all resources are applied in their highest valued combination of end uses, both currently and in the future. Value in this context includes not only commercial value but also 'unpriced values'*[2]." (*Morris et al, 1988*

[2]According to Sinden and Worrell (1979), pp 4-11, value is used as a measure or indicator of relative importance. The value of something is derived basically from some need or desire which it has the capacity to satisfy. 'Unpriced' in this context refers to goods and services whose value cannot be measured in monetary terms; for example intangible or environmental goods.

pp 5-6).

From a land degradation perspective, the degree of degradation which is optimal may not be zero. If the costs of decreasing the level of land degradation are greater than the benefits that would be received (from increased production, for example) then it will be rational for farmers to select land-use practices that result in some positive level of human-induced land degradation.

When the effects of land-use practices are not confined within property boundaries, the costs of land degradation and the benefits of land restoration strategies may also be transferred across these farm boundaries. In the case of dryland salinity, difficulties involved in achieving economic efficiency arise because the decision to clear or revegetate, made by individuals and the community, are linked by the physical characteristics of the groundwater hydrology. All parties acknowledge that their agricultural practices are affecting a common aquifer, but in the absence of institutions that permit collective decision about groundwater management, each individual or group assumes that neighbours will place private interests first. The result, under situations of scarcity, may be socially non-optimal groundwater levels caused by *externalities*, the source of which lies in the producer's ability to influence the level of the watertable, and transmit the costs associated with rising watertables to other areas of the catchment. Thus the watertable represents the form of *common property (Hodge, 1982; Lemoine & Gotsch, 1985).* The dryland salinity problem, therefore exhibits a number of characteristics which indicate the presence of *market failure*. That is, market forces fail to provide incentives which encourage land-users to take into account the full repercussions of farmer's land-use practices.

4. Overexploitation and the "Self-interested Economic Individual"

Under the traditional neoclassical paradigm, different ownership structures are present in society which may affect the extent and management of common property resources. In the case of dryland salinity, the management of salt affected land may differ depending on whether the area is characterised by a *private property*, *common property*, or *open access* situation.

Under a private property situation, the property rights to that resource belong entirely to a particular real or legal person. The sole owner manages the resource optimally by considering all the costs and benefits of additional tree clearing on groundwater levels, and internalising the costs that would normally be imposed on other users that may occur under an open access situation (Stevenson, 1991).

Common property is a form of resource ownership with the following characteristics:

i. *"The resource unit has bounds that are well defined by physical, biological and social parameters.*
ii. *There is a well delineated group of users, who are distinct from persons excluded from resource use*
iii. *Multiple included users participate in resource extraction.*
iv. *Explicit or implicit well-understood rules exist among users regarding their rights and their duties to one another about resource extraction.*
v. *Users share joint, nonexclusive entitlements to the in situ or fugitive resource prior to its capture or use.*
vi. *Users compete for the resource, and thereby impose negative externalities on one another.*
vii. *A well delineated group of rights holders exists, which may or may not coincide with the group of users."* (Stevenson, 1991, p 40)

Open access, alternatively, refers to a *"depletable, fugitive resource characterised by rivalry in exploitation; it is subject to use by any person who has the capability and desire to enter into harvest or extraction of it; and its extraction results in symmetric or asymmetric negative externalities"* Stevenson, 1991, p 9). According to Stevenson, open access leads to under investment in common improvements of the resource-base due to a divergence between those who invest in the improvements and those who reap the benefits of that investment.

In the case of open-access, with many small farms in the catchment, each trying to maximise individual net present value of agricultural production, the individual farmer would have little or no incentive to place a value on the conservation of the common resource being used. Hence the marginal user cost[3] of clearing the land and further raising the watertable would be zero and the resource would be degraded more rapidly than that level which is socially optimal. The clearing/revegetation process would be based on decisions in which current profits were maximised, with no regard for future users of the resource. For example, as explained by *Hardin (1968)*, in his traditional theory of common property[4], *"each man is locked into a system that compels him to*

[3]"User cost" refers to the present value of foregone future extraction benefits (or increased future extraction costs) caused by current resource exploitation. (Stevenson, 1991)

[4]The term Common Property, in Hardin's context, is used as if it were synonymous for limited or open access.

degrade the land even further, without limit - in a world that is limited. (Hence) freedom in a commons brings ruin to all".

By removing property boundaries and modelling the catchment as one farm, where the use of resources is determined solely by that farm, the externalities associated with dryland salinity will be internalised and, by equating marginal user cost to marginal value product, a socially optimum level of salinity can be derived. This is identical to the private property outcome, in which all the costs and benefits, both current and future, are accrued to the one landholder. Thus, by treating the catchment as one farm, the socially optimal level of resource use can be determined.

In between these two levels of resource use lies the common property outcome. The level of exploitation that would occur under this situation would be less than that under the open access outcome due to the existence of a well-delineated group of users of the resource. It would not, however, result in a level of exploitation that would be as low as that which would arise under the private property outcome, because users will still compete for the resource, thereby imposing negative externalities on one another.

5. Extending Beyond the theory of "Self-Interested Individuals"

The standard economic assumption of the 'self-interested economic individual', poses three key difficulties which render it unreasonable on empirical grounds *(Runge, 1986, p628)*

i. The assumption of dominant free-rider behaviour[5] ignores the possibility for *co-operative rules*, unless they are imposed and enforced from outside[6]

ii. By ruling out the importance of changing expectations of others' behaviour, conventional utility maximisation theory fails to capture the *interdependence of decisions* within an economy, and

iii. By overlooking the importance of mutual expectations in the formulation of individual strategy, it fails to deal explicitly with problems of uncertainty regarding the actions of others *(Runge, 1981)*.

Traditional economics seeks to determine mechanisms (mainly price) that will lead to

[5]The results of excessive salinity caused, for example, by over-clearing, arise independently of the expectations of each individual regarding the actions of others. (Runge, 1986, p628).

[6]According to *Runge (1981)*however, co-operative institutional rules are endogenous adaptive responses to problem of uncertainty regarding the expected actions of others, and enforcement from outside is a second order solution that may be implemented when these co-operative strategies are ineffective. This game theoretic formulation of common property externalities is referred to as the *'Assurance game'*. (p604)

the most efficient allocation of resources that allocation most able to satisfy people's wants. However, it sees these wants as being centered on self-happiness. Such conventional utility maximisation theory of the *self-interested economic individual* maximising his own narrowly defined utility assumes that the competitive exploitation of a common property tends to be economically inefficient and anti-conservationist due to individual incentives to cheat.

According to Margolis (1982), *"in the presence of public goods, the behaviour of a self interested 'economic individual' conflicts with everyday observations"*. Such conventional utility maximisation theory, however, does not consider the possibility that individuals act according to some moral principle that requires them to take account of other people's interests *(Sugden, 1984, p773)*. These moralistic actions can give rise to a more common property outcome, rather than the traditional neoclassical open access outcome, in which the costs and benefits to other users of the resource are taken into account in the decision making process.

The finding that people have several wants, including a commitment to live up to their moral values, and that these values cannot be neatly ordered or regulated by prices *(Etzioni, 1988)*, has given rise to alternative models that incorporate aspects of common property solutions.

Four theories, not based on the conventional utility maximisation theory, are presented here, which help to explain why individuals do not always free-ride, but instead act according to moral principles and norms that requires them to take account of other people's interests. One such theory, presented by Margolis (1982), is the theory of non-selfish behaviour. *"In this theory each individual has two utility functions. One kind of utility - 'S utility' - is essentially the individual's self-interest; the other - 'G utility' - is the individual's conception of the welfare of the 'group' to which he feels he belongs. The individual allocates his resources between these two departments of life - or two selves - according to some notion of 'fair shares'.* *(Sugden, 1984, p774)*. Notice that this theory is one of *altruism* because individuals act non-selfishly and are motivated by the concern for other people's welfare. In short Margolis assumes that humans pass moral judgement over their urges. This theory has been extended by Etzioni (1988) to integrate the self-oriented, rational behaviour model, that forms markets and rational decision-making, with society and personality:

1. Where the neoclassical paradigm assumes that people seek to maximise one utility

(whether it be pleasure, happiness, consumption, or merely a formal notion of a unitary goal), *Etzioni (1988)* assumes that people pursue at least two irreducible 'utilities', which have two sources of valuation: pleasure and morality;

ii. The neoclassical paradigm which is based on the assumption that people render decisions rationally is replaced by the assumption that people typically select means, not just goals, first and foremost on the basis of their values and emotions; and

iii. The neoclassical assumption that the individual is the decision-making unit, is replaced to assume that social collectivities (such as ethnic and racial groups, peer groups at work, and neighbourhood groups) are the prime decision-making units. *Etzioni (1988)*

The third approach is one of *unconditional commitment*, and is based on the assumption that people follow a morality, not of altruism but of *cooperation* where individuals pursue self-interest subject to moral constraints. It is based on the following rules: Suppose that *I* is the group of individuals who benefit from the public good, and consider any person *i* who is a member of *I*. Let *i* choose the level of effort that he would most prefer that every member of *I* should make (the same for each person). Then *i* is obliged to make at least this effort. *(Sugden, 1984, p774).*

This principle, however, requires each individual to make whatever contribution he would wish others to make - irrespective of whether the others actually make this contribution. Such a theory is morally objectionable, especially in circumstances where there is reason to doubt that anyo lse in the group will contribute anything towards a certain public good irrespective of what you do *(Sugden, 1984, p774).*

The fourth approach, which is an extension of the unconditional commitment approach, is one of *reciprocity*. This principle never requires an individual to contribute more than other people in the 'group', thus overcoming the problem of unfairness that arises in the unconditional commitment case above. In this approac *G* is *any* group of individuals of which *i* is a member. Suppose that every member of *G* except *i* is making an effort of at least *e* in the production of some public good. Then let *i* choose the level of effort that he would most prefer that every member of *G* should make. If this most preferred level of effort is not less that *e*, then *i* is under an obligation to the members of *G* to make an effort of at least *e*. This is referred to as the principle of *reciprocity*.

All these theoretical approaches are important in determining the effects of both endogenous and exogenous co-operative institutional rules on free-riding and the exploitation of common pool resources. The *degree* of co-operation gives rise to models that incorporate aspects of common property solutions that are not incorporated into open access models of the self-interested economic individual. In the case of dryland salinity, for example, the effect of non-cooperation by some landholders in a catchment will have varying impacts on the productive capacity of the remainder of the catchment depending on whether the non-cooperative farmer is located in a recharge or discharge zone. The effect of non-cooperation behaviour and the modelling techniques available for estimating the effects of non-cooperation is discussed below.

6. Simulating alternative economic and hydrogeological management options

The preceding section dealt with the differences between common property and open access situations that arise under traditional and alternative theories of economic behaviour. By differentiating between such theories and incorporating these into the calibrated transient model of groundwater flow, the effects of a range of alternative landuse option to manage dryland salinity in the NSLCD can be simulated. The effectiveness of each landuse management option can be gauged in terms of the effects on the NSLCD aquifer, in particular groundwater levels, and the effects on the net revenue to the catchment.

Ideally, the aim of the predictive simulations is to compare the current landuse situation with the long run effects (both economic and hydrogeological) of alternative landuse options including:

i. the *total revegetation* of the catchment with high water-using trees. This will represent the *upper limit on groundwater reductions* over time. However, as the commercial benefits from tree planting are expected to be limited, net returns to the landholder are also expected to be low, and thus is not expected to be a preferred landuse practice.

ii. using crops and pastures that yield the *highest current net returns to agriculture* across the catchment, irrespective of the effects this planting strategy would have on future groundwater levels. This would be representative of the traditional neoclassical open access situation. Under this option, profits would be expected to be high in the short-run, but would decrease as groundwater levels rose and potential yields declined. By comparing this option with the current landuse situation (which assumes some degree of co-operation takes place), one can determine the extent of the divergence between the traditional open access situation and the common property solutions that incorporate moral behaviour and altruism; and

iii. altering land use practices, taking into account the location of recharge and discharge zones, groundwater flow direction and depth to groundwater. Such a land management option is representative of the common property solution that incorporates alternative economic paradigms, in which decisions are not only based on the traditional neoclassical factors that form markets and rational decision-making, but also on factors that form society and personality, altruism, cooperation, reciprocity and morality. The degree of co-operation (including the effects of non-cooperation) may also have an effect on future groundwater levels and economic returns. Economic and social factors may prevent farmers from adopting land-use practices which would benefit the catchment as a whole. By altering agricultural practices on some recharge areas and allowing other areas to remain unaltered, the effects of planting location on recharge reduction, can be estimated.

Hence, hydrogeological and economic modelling in the NSLCD enables various land-use management practices to be gauged in terms of their long-run and spatial effects on groundwater levels, and net returns to farmers. Such models would help the community, farmers, landcare groups and the government make decisions in relation to the management of this common property problem. Moreover, these models are generic and could therefore be used for the management of dryland salinity problems elsewhere in Australia as well as overseas. However, major limitations of this methodological approach has been the shortage of basic data. For example, model calibration requires the use of long-run, regularly collected potentiometric data, which was not always available throughout the NSLCD. In addition, estimating the effects of recharge by rainfall and discharge by evapo-transpiration on groundwater levels is complicated by the site-specificity of this data, and differs greatly across the catchment. Estimating discharge through evapotranspiration under different crops and pastures for example, will depend on a complex array of hydrogeological, biological and climatic factors including soil-type, rooting depth, topography, planting density, temperature, rainfall and groundwater depth, which differ greatly over time across the catchment.

7. Bibliography

Appleyard, S., (1989)., "The Hydrogeology of the North Stirling Soil Conservation District"., Draft Hydrogeology Report., Geological Survey of Western Australia.

Etzioni, A., (1988)., "The Moral Dimension - Toward a New Economics"., Macmillan Publishers

Gomboso, J., and Ghassemi, F., (1992)., "Groundwater Modelling and Optimal Salinity Control in the North Stirling Land Conservation District, Western Australia - A Hydrogeological and Economic Perspective"., Mathematics and Computers in Simulation., Vol. 33., pp 609-614.

Hardin, G.J., (1968)., "The Tragedy of the Commons"., Science., Vol. 162 (3859)., pp 1243-8.

Hodge, I., (1982)., "Rights to Cleared Land and the Control of Dryland-Seepage Salinity"., Australian Journal of Agricultural Economics., Vol. 26, No. 3., pp 185-201.

Lemoine, P.H., and Gotsch, C.H., (1985)., "Water Resource Development in the Salinas Valley: Economic and Hydrology in a Closed Control Model"., Food Research Institute Studies., Vol. 19, No. 3., pp 293-33.

Lennard, R., and Nulsen, R.A., (1985)., "Climate, Physiography, Geology, Hydrology and Land Use in the North Stirlings Area - A Precursory Report"., Western Australian Department of Agriculture., Technical Report.

Margolis, H., (1982)., "Selfishness, Altruism, and Rationality"., Cambridge University Press

Morris, P., Wilks, L., and Wonder, B., (1988)., "Natural Resource Management: Some Economic and Policy Considerations"., Australian Bureau of Agricultural and Resource Economics., Paper presented to the Australian Institute of Valuers and Land Administrators, Country Conference, bowral, 14-16 October.

Runge, C.F., (1986)., "Common Property and Collective Action in Economic Development:., World Development., Vol. 14, No. 5., pp 623-635.

Runge, C.F., (1981)., "Common Property Externalities: Isolation, Assurance, and Resource Depletion in a Traditional Grazing Context"., American Journal of Agricultural Economics., Vol. 63, pp 595-606.

Sinden, J.A., and Worrell, A.C., (1979)., "Unpriced Values - Decisions without Market Prices"., John Wiley & Sons, Inc, New York.

Stevenson, G.G., (1991)., "Common Property Economics - A General Theory and Land Use Applications"., Cambridge University Press.

Sugden, R., (1984)., "Reciprocity: The Supply of Public Goods Through Voluntary Contributions:., The Economic Journal., Vol. 94, December., pp 772-787.

Western Australian Department of Agriculture., (1988)., "North Stirling Land Conservation District Situation Summary"., Unpublished Report., Katanning Department of Agriculture, Western Australia.