Efficiency Policies for Salinity Management: Preliminary Research from a Spatial and Dynamic Metamodel

Tennille Graham,
Ben White,
David Pannell

Contributed Paper presented to the 47th Annual Conference

Of the Australian Agricultural and Resource Economics Society

At

Fremantle,

February 12-14, 2003

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Preliminary Research from a Spatial and Dynamic Metamodel

Authors: Tennille Graham, Ben White and David Pannell

School of Agricultural and Resource Economics, University of Western Australia
CRC for Plant Based Management for Dryland Salinity

Abstract

Dryland salinity, as an externality, has an impact on various public assets, including roads, biodiversity and public water supplies. This has been seen as an important justification for government to take action and internalise the pollution. Economic policy instruments have been identified as a potential solution to the problem, as they may achieve environmental goals at least cost to society. This paper presents a spatial and dynamic model which aims to compare economic instruments for land use change to abate the off-site impacts of salinity on public assets. Preliminary research is presented, along with a discussion of the model's structure.

Keywords: dryland salinity, economic modelling, meta-modelling, policy

Introduction

Numerous models have been applied to investigate various aspects of dryland salinity in hydrology, plant sciences, soil sciences and the social sciences. There appears to be no consensus as to which models give the best representation of this phenomenon. Due to the uncertainty over the appropriate models to apply, economists have attempted to model the hydrological impacts of dryland salinity, in an effort to understand the impact on agents affected. These models in most cases assume a simple 'bucket' process, where water enters the ground up hill and exits down hill, causing dryland salinity. This approach is obviously a simplication, ignoring lateral flow, soil types or geological features of the landscape. These simplified models have been developed as hydrology models were judged to be too large and complex to allow economic analyses.

One method for making these large, complex hydrological simulation models manageable is metamodelling. It has been used to reduce the complexity and execution time of hydrological models to allow biophysical and economic analyses. The purpose of this paper is to present a conceptual spatial and dynamic metamodel of a catchment in the Western Australian Wheatbelt affected by dryland salinity, with the eventual goal of identifying economic instruments that are efficient at altering landholders' land use to reduce dryland salinity in the area.

First a brief review will be given of past studies at modelling the hydrological component of dryland salinity for economic analyses. Following this, metamodelling will be explained as an alternative method of including the hydrology component into economic analysis. Current research will be presented from the metamodelling of a hydrology simulation model for the WA Wheatbelt.

Previous Hydrology Models for Dryland Salinity

The majority of past hydrological models of dryland salinity for economic modelling have been based on broad and simple assumptions of the hydrological systems of an area (eg Quiggin, 1986; Salerian, 1991; Barton, 1992; Cacho et al., 2001; Greiner et al., 2001; van Bueren et al., 2001). However, a few studies (e.g. Gomboso et al., 1992; Pavelic et al., 1997; Bell et al., 2001) have employed sophisticated hydrology models to predict the occurrence of dryland salinity. In many instances the economic analysis is not a major component of the study (due to the complexity of the hydrology component) and tends to be a benefit-cost analysis or net present value study.

Subsequently, there is a trade-off between the complexity and effectiveness of the hydrology model and the economic model. As such there is a need to develop a method to reduce the complexity of hydrology models to allow a comprehensive economic analysis of dryland salinity case studies. One such method is metamodelling, which is described in the following section.

Metamodelling

Metamodels are models of models. Process-based simulation models that are used in hydrology are large complex, nonlinear models with temporal and spatial relationships. Metamodelling involves designing a series of model runs (treatments) to develop an input-output relationship from the process model. This relationship is then applied to regression analysis to develop a simplified regression model (the metamodel). The resulting metamodel can then be used in a mathematical programming model designed to determine the relative efficiencies of policies (Bouzaher et al., 1993). Depending on the purpose of the analysis, different types of metamodels can exist from the one simulation model including, for example, the analysis of parameter sensitivities (Blanning, 1975) or for model optimisation (Carriquiry et al., 1998). Building such a model can be done with *a priori* technical knowledge or without it.

The advantages of this method includes reduced data requirements, a simpler functional form, less demanding modelling effort and a high integrative potential (Kleijnen, 1992; Haberlandt et al., 2002). However, the disadvantage is a loss of some accuracy and detail. Depending on the problem at hand, this may or may not be a major concern. Generally the need for accuracy in a metamodel is not as great as for a simulation model (Blanning, 1975).

Meta-Modelling for Agricultural Pollution Problems

The application of metamodelling to various agricultural and non-point source pollution problems is relatively recent. However it has been used extensively in social science, engineering and medical disciplines. In most cases, metamodelling has been used to decrease the complexity and time consuming nature of a process-based model to investigate different policy situations. For example, Bouzaher et al. (1993) used metamodelling to evaluate agricultural non-point pollution policies. Their approach was to estimate and validate regression metamodels for the concentrations of chemicals in groundwater and surface water in the US. After generating simulations from the process based model, a simple nonlinear exponential function was adequate to explain and predict the simulation model responses. In turn, the validated metamodel was incorporated with an agricultural economic decision-making model that allowed various weed management control strategies. Bouzaher et al (1993) judged that in this case, if metamodelling was not used, the policy analysis would have been less comprehensive and thus less adequate to deal with the difficult task of policy formulation.

Similarly, Carriquiry et al. (1998) used metamodelling to reduce the complexity of a sheet and rill erosion process model. Their metamodel did have evidence of lack of fit, however the results estimated and predicted by the model were equivalent to the process model. Additionally, Haberlandt et al. (2002) used metamodelling to assess the leaching of nitrogen from arable land into waterways. Their results confirm a strong correlation between the process based model and the metamodel. Kampas et al. (2002) also employed metamodelling of a biophysical model for nitrate pollution to develop a nonlinear optimization framework. Results from two simulation models of nitrate emissions were represented by simple regression models.

Significance for Dryland Salinity

Obviously, metamodelling has been used successfully to represent complex process models of environmental systems. Of particular interest is the use of metamodelling to decrease the complexity of many hydrological models representing nitrogen movement in waterways and chemical transportation in water. These studies, as described above, have been successful in reducing the complexity of these models, but also providing realistic results for policy analyses. This suggests that metamodelling may be useful in decreasing the complexity of hydrology models for salinity. The following section explains the WA Wheatbelt and the occurrence of dryland salinity as an externality, and also why the Date Creek subcatchment was chosen as a representative area of the Wheatbelt.

WA Wheatbelt and the Presence of Externalities

The Western Australian Wheatbelt

Salinisation of the WA Wheatbelt is controlled by hydrogeological processes that affect the distribution of recharge and control the transmission of water and pressure within the saturated zone of the soil (Coram, 1998). Climate also plays a major part in the distribution of saline areas; there are negligible areas of salt-affected land in regions with an average rainfall of greater than 1100mm/yr (Coram, 1998). Within the Wheatbelt there are three broad drainage divisions:

- Eastern and Central Wheatbelt: ancient drainage lines contain extensive chains of salt lakes, characterised by poor drainage and lateral movement. Rainfall is low in this area of the Wheatbelt.
- Meckering Line (Western Wheatbelt): west of the Meckering Line there is an increase in slopes and relief, and thus better drainage of the soils.

- Jarrahwood Axis (Southern Wheatbelt): lies approx parallel to the south coast, 80km inland. This area is gently undulating country, associated with broad flat valley floors which are tributaries to zones of salt lakes, which can range from poorly drained to well drained (McArthur, 1991; Tille et al., 1998).

George et al. (2001) conducted an analysis into the responsiveness of various parts of the wheatbelt to different management strategies. Representative catchments were chosen for the Eastern Wheatbelt (North Bandee), Central Wheatbelt (Toolibin) and Western Wheatbelt (Date Creek). The hydrology model used was Flowtube, a model that has been extensively used in the WA Wheatbelt. The results suggested that catchments in the western region would respond to recharge reduction more quickly and to a greater extent than the eastern and central wheatbelts.

The Presence of a Salinity Externality

Dryland salinity can be classified as a spatially distributed pollutant (point and non-point) that has externality effects on many public and private assets in the agricultural landscape. However it has been argued that externalities may not be as prominent as previously believed. Several reasons have been outlined why the external affects of salinity are less important in WA than previously believed, including:

- For a proportion of the landscape, little groundwater moves across farm boundaries;
- Low slopes and low transmissivity of soils means that treatments are sometimes effective only locally;
- Key resources will continue to be damaged for many years even if large scale revegetation strategies are implemented (Pannell et al., 2001).

It may be that externalities are not the primary reason for market failure in response to salinity. Three other causes of market failure proposed by Pannell (2001) are: divergence between public and private discount rates, divergence between public and private attitudes to risk, and the fact that both information and some environmental benefits are “public goods” which may not be adequately provided by the market. The last point may be regarded as an externality problem in that on-farm management may be required to save a high value public asset. Thus the choice of policy instrument is crucial to address this problem.

The research by George et al (2001) tends to support the ideas expressed by Pannell et al (2001), in that the presence of externalities may not be as evident in the Eastern and Central Wheatbelt, but more obvious in the Western Wheatbelt. Suggesting that the application of economic instruments may be more relevant to this area of the Wheatbelt, and other approaches are appropriate to other sections of the Wheatbelt. Therefore, the Date Creek Subcatchment was chosen as a representative catchment for a generic model of the Western Wheatbelt as it has already been extensively modelled and researched. The following section explains the hydrology model, Flowtube, provides a summary of Date Creek and the metamodelling that was conducted.

Regression of a Hydrology Simulation Model

Flowtube Simulation Model

Flowtube was chosen as the representative hydrology model (after extensive investigation into other potential 2D and 3D models) as it has been successfully applied to the WA Wheatbelt (George et al., 2001a; George et al., 2001b) and easily manipulated by the authors. Argent (2001) provides a more in-depth description of the Flowtube hydrology model for the WA Wheatbelt.

The model assumes that the groundwater body can be separated into a number of flow tubes, each of which represents the thickness of the soil above the bedrock and describes a single flow line in a flow net (Figure 1). For each site modelled the flow tube is divided into a number of cells of equal length (this length depends upon the overall length of the flow tube). Groundwater movement between cells is controlled by the Boussinesq diffusion equation:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_x \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)=S_s \frac{\partial h}{\partial t}-R \qquad (1)$$

where this partial differential equation aims to construct a 3D distribution of heads (h) (the pressure exerted by a liquid), hydraulic conductivities (K) and storage properties (S and R) everywhere within the groundwater system (Anderson et al., 1992).

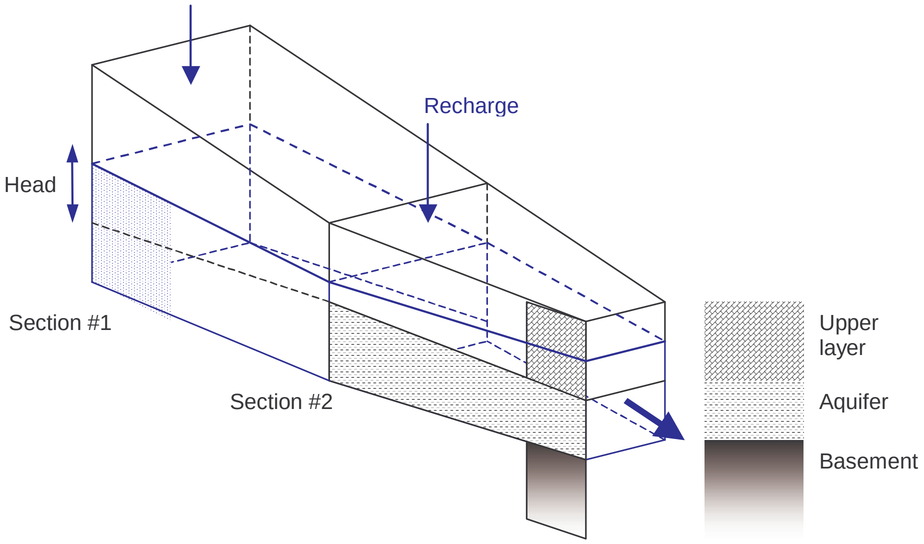

Figure 1: Representative diagram of the Flowtube model. Source: (Argent, 2001)

Initial and boundary conditions are imposed for the differential equation for the starting water level and conditions for each end of the flow tube. Areas at risk of salinising are calculated to occur where the watertable comes within one meter of the soil surface. Each simulation is for a period of 100 years and the watertables converge as equilibrium is reached (George et al., 2001).

For each cell along the flow tube, the annual land use provides the default recharge value. To implement an alternative land use, the recharge value is specified as a proportion of the original annual recharge value. For example, if trees were chosen as a land use, the recharge value may be closer to 0.1, that is, the amount of recharge under trees is one tenth of the recharge under the annual farming system. Additionally, increasing the proportion of area assigned to perennial vegetation is achieved by assigning various recharges rates for each cell along the flow tube.

Date Creek Subcatchment

The Date Creek Subcatchment is one of the most researched catchments in Western Australia. It is a subcatchment of the Blackwood River Catchment, located within the West Arthur Management Zone. The subcatchment is 20km southwest of Darkan in the western Wheatbelt of WA (Figure 2). Grazing annual pastures for wool, lamb and beef production are the predominant industries. Only limited areas of perennial species presently exist at any site, with Date Creek having 20% of its catchment covered by woody vegetation (George et al., 2001). Commercial tree crops (*E.globulus* and *Pinus pinaster*) are currently grown near Date Creek. Its annual rainfall is 600mm/yr and potential evaporation of 1500mm/yr.

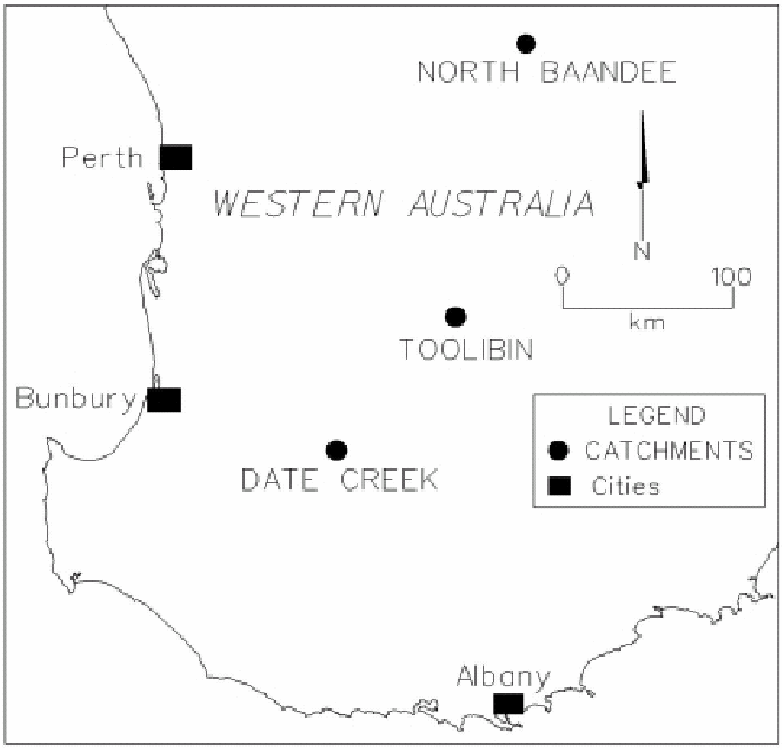

Figure 2: Location of Date Creek Subcatchment, in relation to Lake Toolibin in the Blackwood River Catchment, Western Australia. Source: (George et al., 2001).

Methods

Flowtube Simulation

The Flowtube model was run several times for differing combinations of proportion of perennial cover (0, 5, 10, 15, 20, 40, 60, 80 and 100) and recharge proportions (0.05, 0.1, 0.3, 0.5 and 1). Each simulation was run for 100 years, in 5 year time steps. Results were gathered (in Excel) showing the head of the watertable every 50m along the Date Creek cross section (3300m), for each time step starting at time zero. Figure 3 shows that the simulated result follow a non linear functional form.

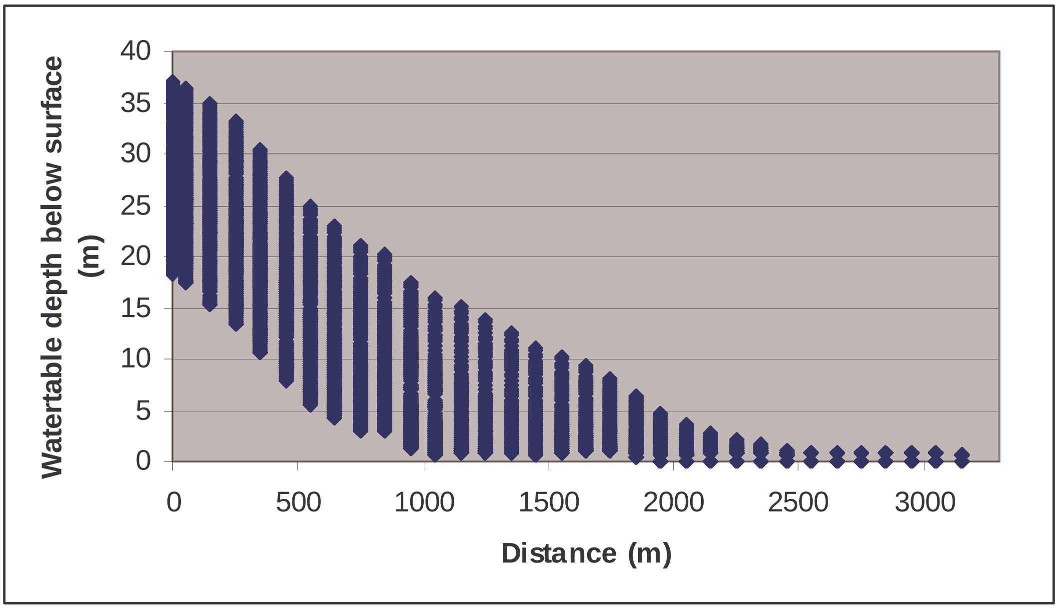

Figure 3: Simulation model output data showing watertable depth over the distance of the cross section.

Estimation Approach

For the analysis, the model developed was an estimation of (1), where the following variables were approximated, where K and R were approximated by the proportion of area covered (C) and proportion of recharge (R) to develop CR; x,y and z was approximated by the distance from start of the cross section (D) and time (T); S and h were approximate by the depth to watertable (W) in meters and head (H) in metres, depending upon the simulation run.

Estimate of the output from the simulation model involved two approaches. The first, two equations approach, was aimed at fitting a model to the change in H_t at D=0, that is the top of the catchment, using a lagged endogenous variable, $H_{t-1,}$ function:

$$H_t = \beta_1 H_{t-1} + \beta_2 CR + \beta_3 CR^2 + \varepsilon \quad (2)$$

Secondly, analyses were conducted to determine if W_t at D=0 would be able to predict W_t at other distances down the cross section. A quadratic functional form was considered to be the most appropriate, as the observed data is obviously non linear (Figure 3). The quadratic equations fitted were:

$$H_{td} = \beta_1 + \beta_2 H_{t0} + \beta_3 H_{t0}^2 + \beta_4 CR + \beta_5 CR^2 + \beta_6 D + \varepsilon \qquad (3)$$
$$H_{td} = \beta_1 + \beta_2 H_{t0}^2 + \beta_3 CR + \beta_4 CR^2 + \beta_5 D^2 + \varepsilon \qquad (4)$$
$$H_{td} = \beta_1 + \beta_2 H_{t0} + \beta_3 CR^2 + \beta_4 D + \varepsilon \qquad (5)$$

The second, single equation approach was to treat the data set as a whole, not as one section determining W_t along the cross section. Time was also included into many of these equations, as the watertable depth occurs specifically one T and D. The watertable depth was determined by the following functional forms:

$$W_{td} = \beta_1 + \beta_2 D + \beta_3 CR + \beta_4 T + \varepsilon \qquad (6)$$
$$W_{td} = \beta_1 + \beta_2 D + \beta_3 D^2 + \beta_4 CR + \beta_5 CR^2 + \beta_6 T + \beta_7 T^2 + \varepsilon \qquad (7)$$
$$W_{td} = \beta_1 + \beta_2 D + \beta_3 D^2 + \beta_4 D^3 + \beta_5 CR + \beta_6 CR^2 + \beta_7 T + \beta_8 T^2 + \varepsilon \qquad (8)$$
$$W_{td} = \beta_1 + \beta_2 W_{t-1,d} + \beta_3 D + \beta_4 D^2 + \beta_5 D^3 + \beta_6 CR + \beta_7 CR^2 + \beta_8 T + \beta_9 T^2 + \beta_{10} T^3 + \varepsilon \qquad (9)$$
$$W_{td} = \beta_1 + \beta_2 W_{t-1,d} + \beta_3 D + \beta_4 D^2 + \beta_5 CR + \beta_6 CR^2 + \beta_7 T + \varepsilon \qquad (10)$$

In (8), only D was cubed as it had the primary influence on the watertable depth.

Results and Comments

Two Equation Method

Table 1 presents the results from the first analysis for (2), (3), (4) and (5). Even though all equations were good fits, according to the adj R2, the residual vs. fitted values plots (for example Equation (4) (Figure 4)), showed that some values were extremely over or underestimated, such that the residuals did not appear as ‘white noise’, suggesting heterosckedasticity. Hence this approach was rejected and the second approach, where the data was treated as a whole, was investigated.

Table 1: Results from (2-5) showing parameter values (t-value), adj R2 and RMS error.

		EQUATION		
PARAMETERS	(2)	(3)	(4)	(5)
Constant	-	-1484.7 (-18.5)	237.6 (257.5)	187.3 (131.5)
H_{t-1}	1.0 (422.4)	-	-	-
H_{to}	-	11.7 (21.5)	-	0.4 (79.3)
H_{t0}^2	-	-0.02 (-20.8)	0.001 (61.2)	-
CR	0.03 (2.7)	-0.05 (-6.8)	-0.02 (-2.6)	-
CR^2	-0.001 (-2.5)	0.001 (4.4)	0.001 (2.2)	-0.0001 (-1.4)
D	-	-0.01 (-506.5)	-	-0.01 (-498.7)
D^2	-	-	-0.00004 (-400.5)	-
STATISTICS				
Adjusted R^2	0.99	0.95	0.92	0.95
RMS Error	1.1	2.6	3.2	2.6

Figure 4: Residual vs. fitted value plot for Equation (4) in first approach.

Single Equation Method

Table 2 displays the results from the functional forms (6 to 10) applied to the entire data set obtained from Flowtube. Obviously (6) was not a good fit, as the observed data does not show a linear trend. Equations (7) and (8) are good fits according to the adj R^2, but their residual vs. fitted value plots (for example figure 5 for equation (7)) showed that the values were extremely over or underestimated, such that the residuals did not appear as ‘white noise’, again suggesting heterosckedasticity. However, (9) and (10) displayed good fits statistically and graphically of the residual vs. fitted values (for example figure 6 for equation (10)). It is obvious that using a distributed lagged variable (W_{t-1}) is the preferred functional form but further analysis is required.

Table 2 Results from (6-10) showing parameter values (t-value), adj R2 and RMS error.

			EQUATION		
PARAMETERS	(6)	(7)	(8)	(9)	(10)
Constant	18.1 (154.8)	26.0 (257.7)	28.6 (281.8)	1.8 (18.0)	2.0 (21.9)
W_{t-1}	-	-	-	0.9 (302.1)	0.9 (300.6)
T	-0.03 (-4.1)	-0.1 (-6.7)	-0.1 (-7.4)	0.1 (3.9)	-
T^2	-	0.004 (5.0)	0.004 (5.6)	-0.01 (-4.2)	-
T^3	-	-	-	2.7e-04 (5.4)	-
CR	0.04 (7.9)	0.1 (22.1)	0.2 (24.6)	0.02 (7.6)	0.01 (4.9)
CR^2	-	-0.004 (-18.7)	-0.004 (-20.8)	-3.3e-04 (4.4)	-3.3e-04 (-4.5)
D	-0.07 (-159.0)	-0.2 (-230.7)	-0.04 (-160.5)	0.003 (-18.3)	-2.6e-03 (-18.7)
D^2	-	5.4e-06 (165.5)	1.5e-05 (88.9)	1.1e-06 (13.6)	1.1e-06 (13.9)
D^3	-	-	-2.1e-09 (-58.1)	-1.5e-10 (-9.9)	-1.5e-10 (-10.2)
STATISTICS					
Adjusted R^2	0.64	0.88	0.90	0.99	0.99
RMS Error	5.3	3.1	2.8	1.0	1.0

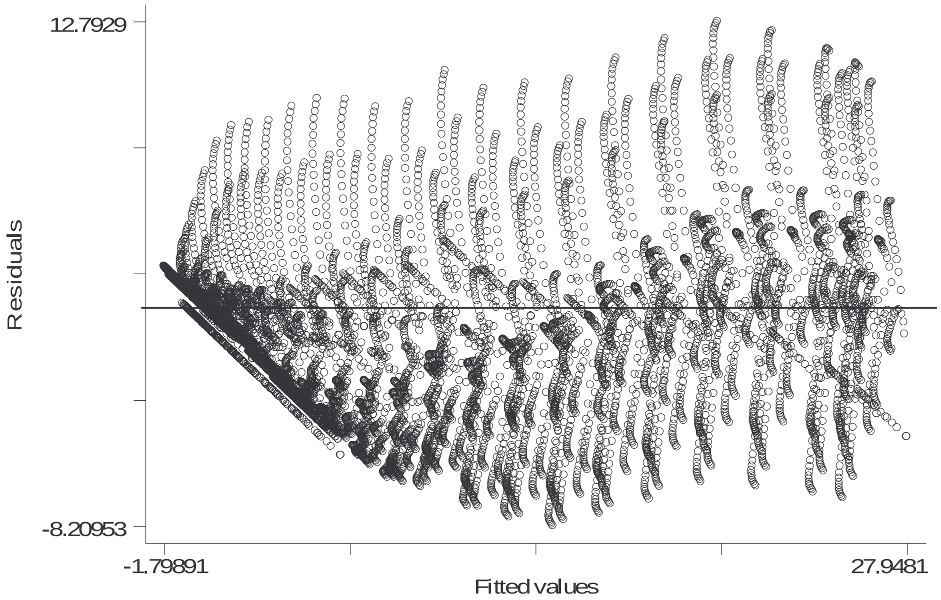

Figure 5: Residuals vs. fitted values plot for Equation (7).

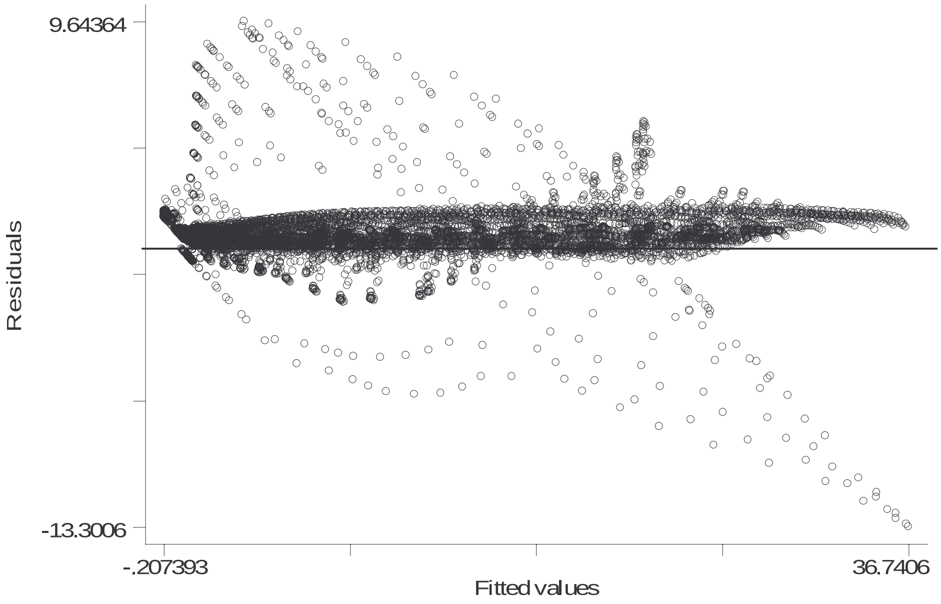

Figure 6: Residuals vs. fitted values plot for the lagged variable function, (10).

Obviously (10) is not complete and still needs adjustment, however figure 6 is encouraging as there are only a few outliers and the evidence of heterosckedasticity is minimal. Further estimation methods were applied to the data, including Tobit, however additional analysis is required.

Future Work

Aim of PhD

The overarching aim of my PhD is to identify the appropriate place for economic instruments or market based mechanisms for salinity management in Western Australia, with potential application to the rest of Australia.

Future Case Studies

This project will develop a generic catchment model to assess the applicability of economic polity instruments to the protection of public assets. Following this, two case studies will be chosen to apply and test the principles acquired from the model; road infrastructure and a Water Resource Recovery Catchment in WA. These case studies will focus on high value public assets which are being severely impacted upon by dryland salinity.

Conclusions

The results presented in this paper are encouraging. They suggest that metamodelling may be a valuable technique to decrease the complexity and time consuming nature of current hydrology model for dryland salinity and to improve its ease of application to economic analyses. Finding the correct functional form is a time consuming task, but with further research and better understanding of the hydrology system, the time taken should lessen. It is hoped that the construction of a hydrology metamodel with its incorporation into an economic model will provide a comprehensive assessment of various economic instruments for dryland salinity reduction or prevention.

Acknowledgements

The authors would like to acknowledge the Grains and Research Development Corporation for their primary financial assistance towards this research, and also the CRC for Plant Based Management of Dryland Salinity for their financial assistance.

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