DEVELOPMENT OF A STRATEGIC SYSTEM DYNAMICS MODEL OF DRYLAND SALINITY

Naeem U Khan and Alan C McLucas
University College, UNSW,
Australian Defence Force Academy,
Northcott Drive, Canberra, ACT, 2600
AUSTRALIA, n.khan@adfa.edu.au

ABSTRACT

Dryland salinity is an insidious problem which progressively degrades arable or marginally productive farming land often to the point that such land becomes incapable of sustaining agriculture in the long term. In Australia, this problem has been exacerbated by the removal of millions of trees to make way for cultivation.

This paper explains how founding research focusing on identification of reference modes of behaviour for dry land salinity has been used to define the requirements for a system dynamics model designed for strategic analysis and to inform choices for strategic management of dryland salinity in Australia's Murray-Darling basin. The system dynamics model constructed on the basis of the previously identified reference modes is described. Its behaviour is analysed and its veracity as an explanation of the causes of dryland salinity, and possible remediation of this widespread and worsening problem, are critically examined.

Key words: System Dynamics, Dryland Salinity, Systems Engineering, Murray Darling Basin, Australia.

3.1 INTRODUCTION

On the global scale, the total area of saline soils is 397 million hectares (ha) and that of sodic soils is 434 million ha. (Based on the FAO/UNESCO Soil Map of the World), these soils are not necessarily arable but cover all salt-affected lands at global level. The problem is spread across continents and Australia is facing a serious environmental problem in the form of salinity. Approximately 5.7 million hectares are reported to be either affected by or at risk of dryland salinity.

Dryland salinity not only affects regional areas but can adversely impact the urban infrastructure as well. On farm impacts include reduction in crop yields, increased farm management and the limited choice of crop production. Adverse impacts of increased salinity levels on the physical infrastructure can be multi-fold. Salinity can affect physical infrastructure in two ways; first the saline water supplies can have detrimental impacts on household and industrial usage of water and the systems that support/facilitate that usages like storage and supply devices. Second, the high water tables associated with salinity prone areas can have detrimental impacts on the communication as well essential supplies networks. It can also reduce the value of tourism and aesthetic resources and can introduce marked changes in the stream and wetland ecology.

In Australia, dryland salinity has developed over time as a result of the feedback interactions among various climatic, geographic, environmental and human factors. Time delays involved in land-use change further add to the complexity of the problem as do the land use decisions. There is abundance of literature focusing on hydrological modelling and integration of hydrological models with the biological and economic models. But the counterintuitive nature of the problem's dynamic behaviour suggests a need for exploration from a holistic perspective.

This paper uses the case of dryland salinity in the Murray Darling Basin to explore dryland salinity causes from a systems perspective. First the salinity problem and its significance is described from a global as well as Australian perspective. The study areas Murray darling basin is explained with important variables that are utilized in the later analysis. A simulation model was developed to aid the analysis. The process of model development is described and model results are analysed.

3.2 DRYLAND SALINITY AND ITS CAUSES

The Environmental protection agency of the New South Wales defined dryland salinity as

> *accumulation of salt in soil and water of non-irrigated areas, caused by clearing trees and vegetation on out-flow zones for saline watertables; the uptake of water by plants is reduced allowing the watertable with soluble salts to rise, killing plants and creating bare areas prone to erosion*.

Salts occur naturally at high levels in the subsoils of most Australian agricultural land that is referred as primary salinity. Secondary dryland salinity refers to the accumulation of salt due to impacts of human activity systems in non irrigated areas.

White (1997) has described dryland salinity causes as:

> *Extensive removal of deep rooted native vegetation has occurred in the southwestern sector of Western Australia, in South Australia, in Victoria and southern New South Wales, and on parts of the western slopes of great dividing range northwards into Queensland. Its replacement with crops of pastures has upset the water balance over large areas. Rising groundwater has mobilized salts causing salinization of soils. Seepage of groundwater into rivers has increased their salinity, polluting the major source of domestic and irrigation water supplies.*

This main causes described in the Australian Dryland Salinity Assessment. are also based on the similar understanding. Some of the causes depicted in the main stream literature are listed below:

- Australia is an ancient continent. Over millennia, it has accumulated sediments and salts through weathering processes. Some of the salts are released from its weathering rocks (particularly marine sediments) but most are carried from surrounding oceans in rain. Overtime, salt stores have been developed that are distributed widely across the semi-arid and arid regions.

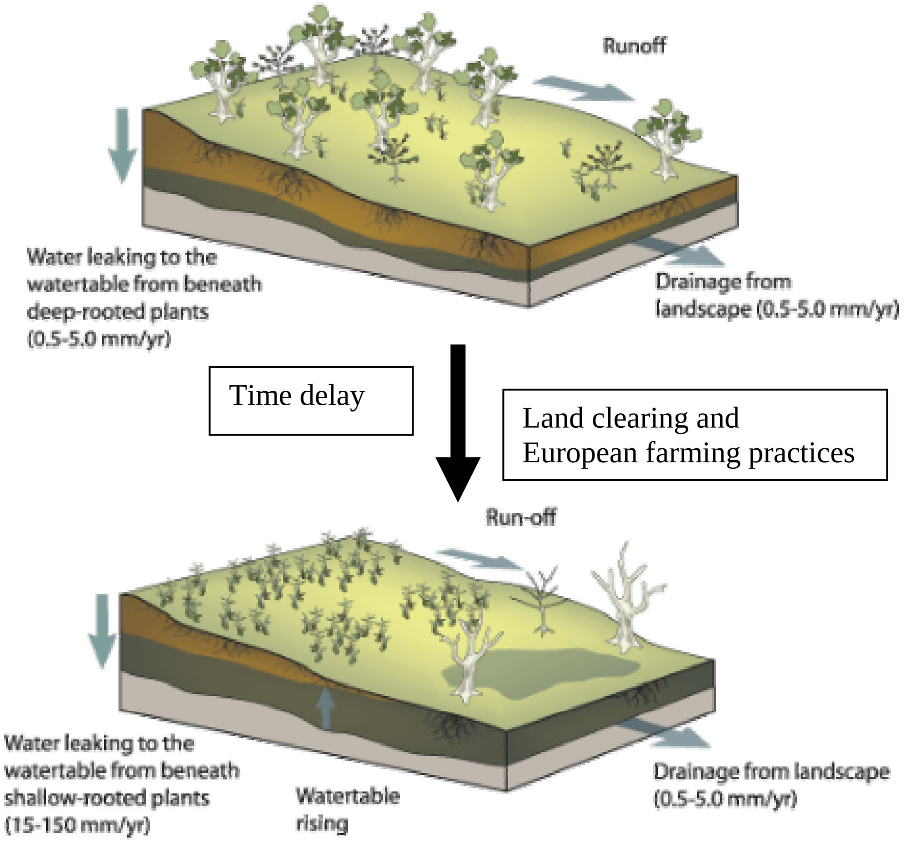


Figure 1. Linkages between land clearing and rise in watertable. Prepared from (White 1994; White 1994; White 1997)

- Changes in land use since European settlements, has exacerbated Australia's natural salinity. Native vegetation has been replaced with crops and pastures with shallow roots. Prior to European settlement, groundwater tables in Australia were in long-term equilibrium. In agricultural regions, settlers cleared most of the native vegetation and replaced it with annual crop and pasture species, which allow a larger proportion of rainfall to remain unused by plants and to enter the groundwater (George, McFarlane et al. 1997; Walker, Gilfedder et al. 1999).

- Water leaking beneath the root zone and entering internal drainage and groundwater systems has increased so that it now exceeds the capacity of the system to discharge additional water to rivers and streams. Patterns and rates of groundwater change vary widely but most bores show a rising trend, except where they have already reached the surface or during periods of low rainfall. Common rates of rise are 10 to 30 cm/year. (Ferdowsian 2001).

Since more water is enters the system than leaves it, watertables rise bringing dissolved salts with it. All this process is depicted in the Figure 1.

3.3 AN INTRODUCTION TO THE STUDY AREA: MURRAY DARLING BASIN

Murray Darling Basin (MDB) is situated in the southeast of Australia. It covers 1,061,469 km^2 , consists of the tributaries of the Murray and Darling Rivers and extends through four states, i.e., New South Wales, Queensland, Victoria and the South Australia. The greater portion of the Basin is formed of extensive plains and low undulating areas mostly below 200m above sea level. It has range of climatic conditions and natural environments from the rainforests of the cool and humid eastern uplands to the temperate Mallee country of the southeast, the inland subtropical areas of the far north to the hot, dry semi-arid and arid areas of the far western plains. Figure 2 shows the main features of the Murray Darling Basin.

1.9 million people live in the Basin. Agriculture is the dominant activity of the Basin. Agriculture is practiced both on the irrigated areas as well as dryland areas. The total area of the crops and pastures irrigated in the MDB is 1,472,241 ha. Agricultural land use consists of crops, pastures and grasses. The total area devoted to crops is 7,137,303 ha. The main crops grown include wheat, barley, rice, oilseeds, cotton and number of horticultural commodities. Commercial agriculture is undertaken on the 51,672 farms. Dryland salinity is a major issue that is threatening productivity, livelihood and infrastructure. Figure 3 shows the areas affected by the dryland salinity in the Basin.

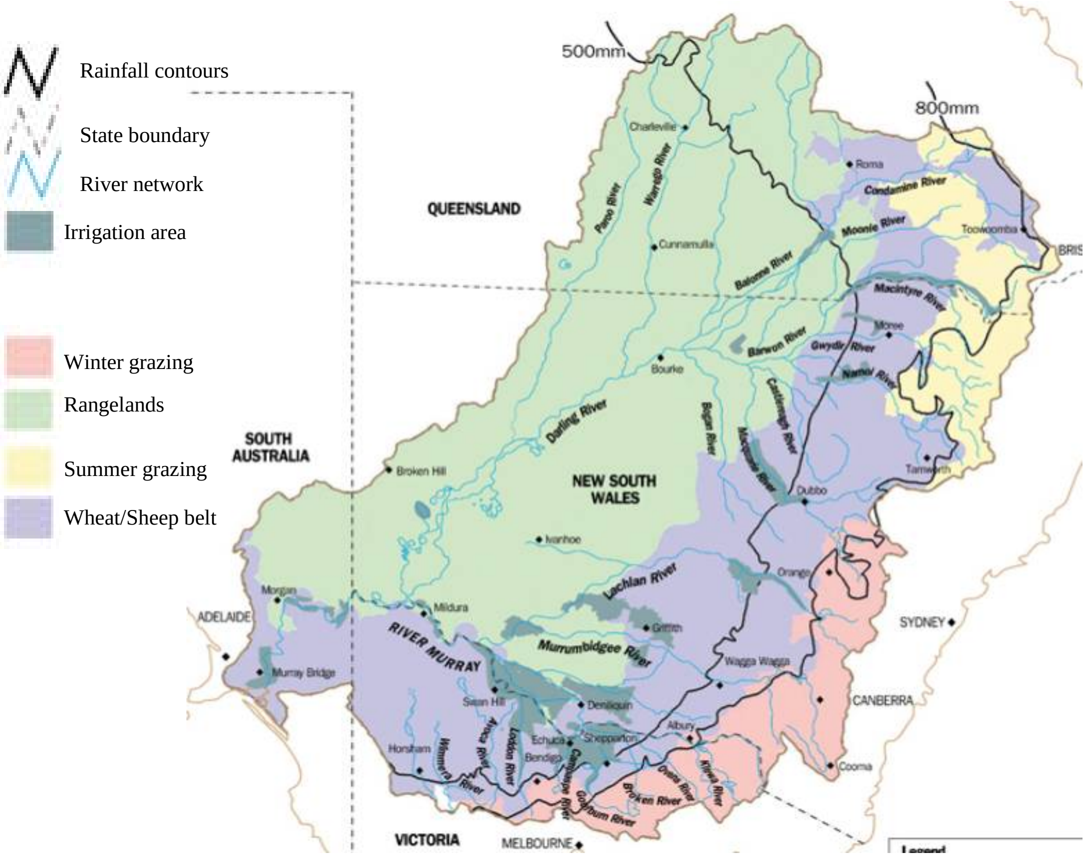


Figure 2. Key Features of the Murray Darling Basin (MDBC 2002)

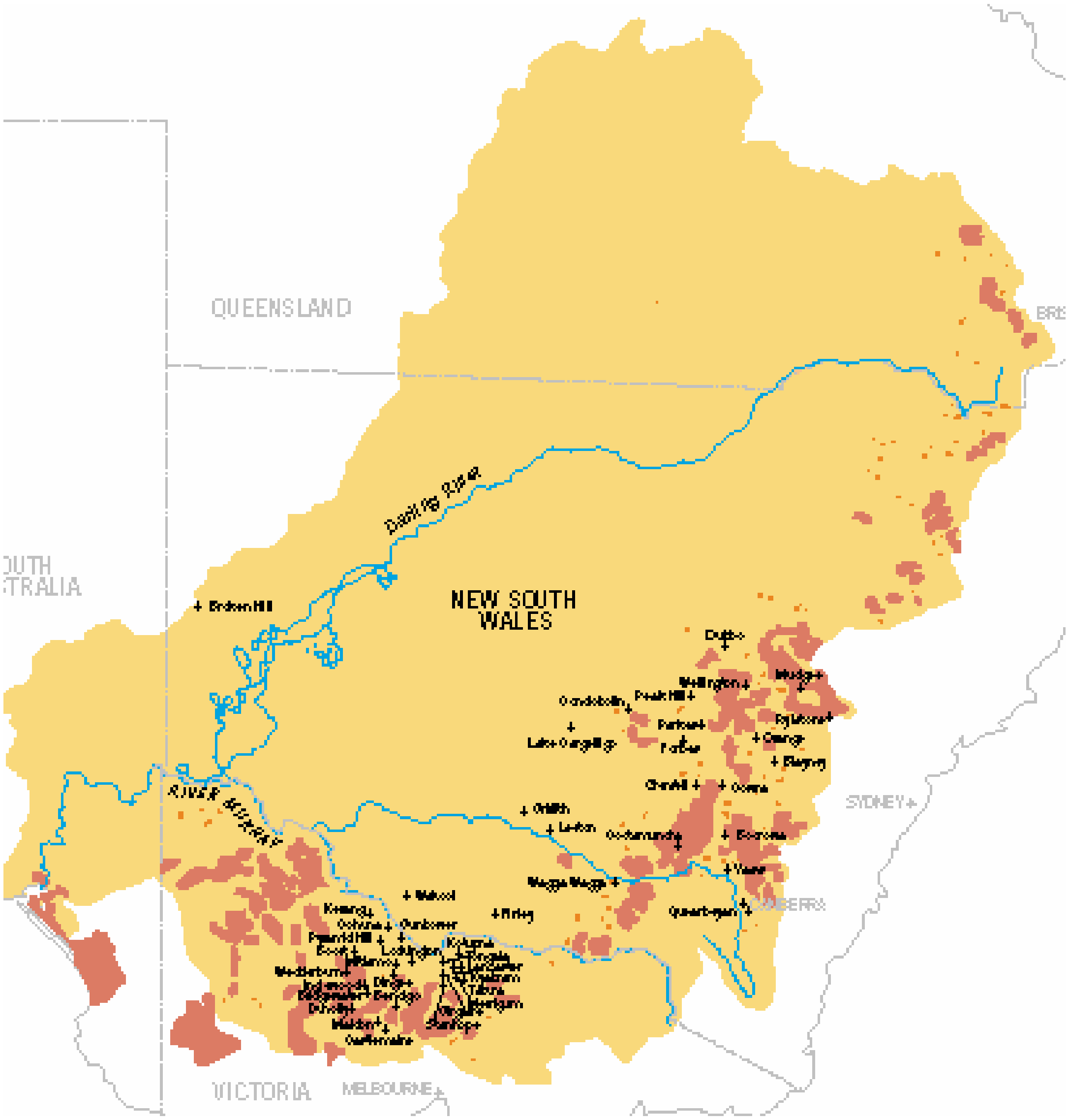


Figure 3. Extent of Dryland Salinity in the Murray Darling Basin. Brown areas indicate dryland salinity affected area (Source: MDBC)

The landscape in the Murray Darling Basin has changed overtime. The major human induced impacts had been settlement and land clearing for agricultural urban and industrial uses. Agriculture is one of the major sectors for land use change (Crabb 1997). A major expansion in agricultural development (Figures 4) during 1950s to 1980 was due to extensive clearing and increase in cultivated area.

Land clearing started in the Murray Darling Basin many years ago and it is still continuing. The term land clearing refers to removal of the natural cover (e.g. forest) from the land for alternative uses. The current motivators for land clearing include land availability, clearing controls, environmental and social influences, financial and Institutional incentives, agricultural research and development, and market forces (AGO 2000). One of the causes of land clearing was conditional purchases. For example from 1860's to 1960's leases and conditional purchases were issued on the proviso that a certain percentage of tree cover was to be removed each year (BRS 2000). Graetz, Wilson et al. (1995) assessed that, at national level, 1,029,640 sq km have been thinned and cleared within intensive landuse zones and most of this is in the Murray Darling Basin.

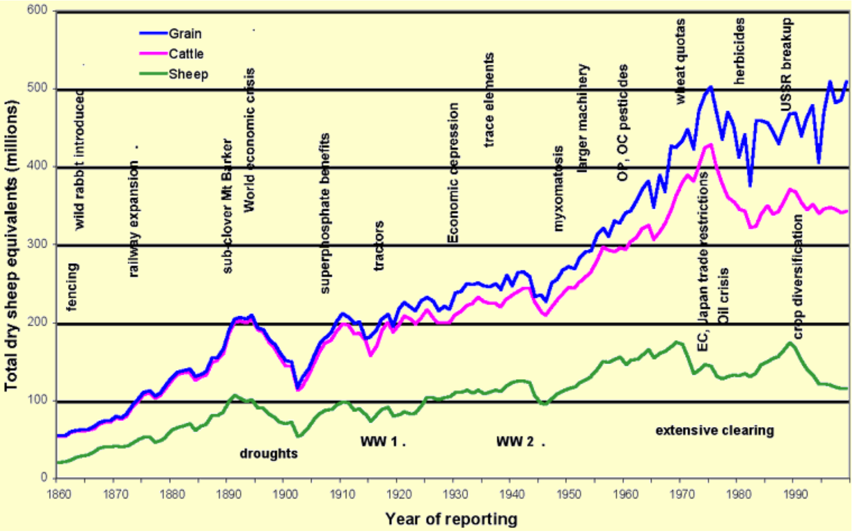


Figure 4. Historical trends of agricultural industry development, converted to dry sheep equivalents (DSE) with major influences (NLWRA 2001)

Another impact of agricultural development is an increase in diversions from the Murray Darling River (Figure 5). These river extractions have increased multi-fold over the last five decades. The amount of water presently taken from rivers is not ecologically sustainable (Toyne 1995 cited in Crabb 1997:53). The following excerpts from literature depict the picture:

- *The continuing saga of the extraction of massive amounts of irrigation water from inland rivers to satisfy the escalating demands of the irrigation industry is Australia's most serious, and ultimately most disastrous water related issue .*

- *The impacts of land clearing and management of the Murray Darling Basin Waters by construction of dams and canals have lessened the variations in flow and salinity. However, the exploitation of the waters has reduced the capacity of the rivers to carry salt to the sea without prejudice to water users in the downstream reaches and has delivered a far higher salt load to the river systems (Evans, Newman et al. 1996).*

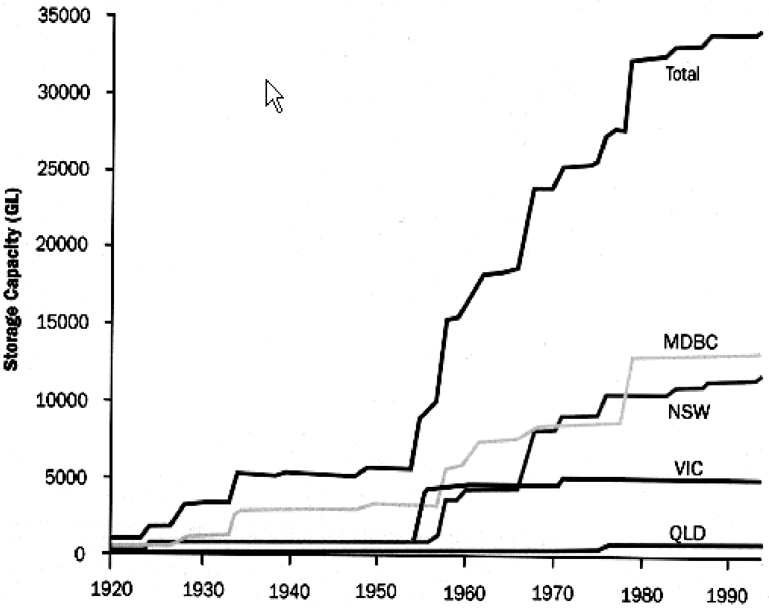


Figure 5. Storage Capacity in the Murray Darling Basin (Crabb 1997)

Despite of all these efforts for development, the terms of trade of the Australian farmers worsened of which Murray Darling Basin is not an exception. Australian farm incomes are shown in the Figure 6.

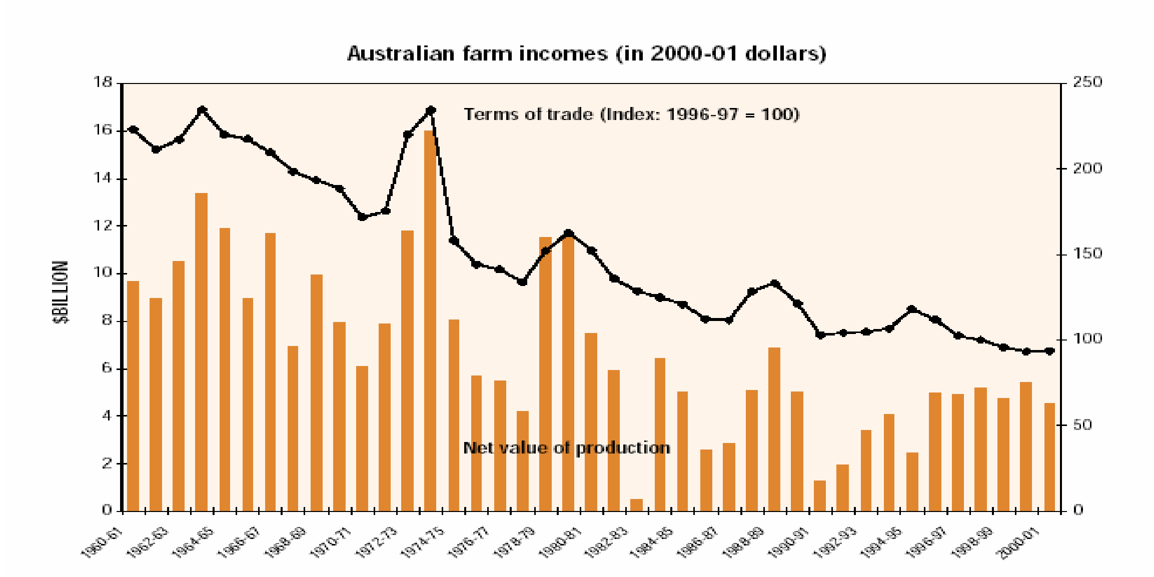


Figure 6. Australian Farm Incomes

3.4 REFERENCE MODES

To identify a reference mode of the problem, a methodology consisting of learning cycles suggested by Saeed (2002) was used. The method provided a step-by-step approach towards development of reference modes and involved five learning cycles. Each learning cycle consisted of four steps. The first learning cycle started with the examination of available time series data. During the process, each learning cycle yielded an intermediate product. The intermediate products of this learning process were domain boundary, preliminary system boundary, preliminary model boundary and model boundary. At the end of the fifth learning cycle, a reference mode was developed. This reference mode consisted of a graph showing a pattern of the past behaviour as well as likely future behaviour of the variables. The reference modes so prepared were presented at the International System Dynamics Society Conference in Oxford 2004 (Khan, McLucas et al. 2004), and are shown in the Figure 7.

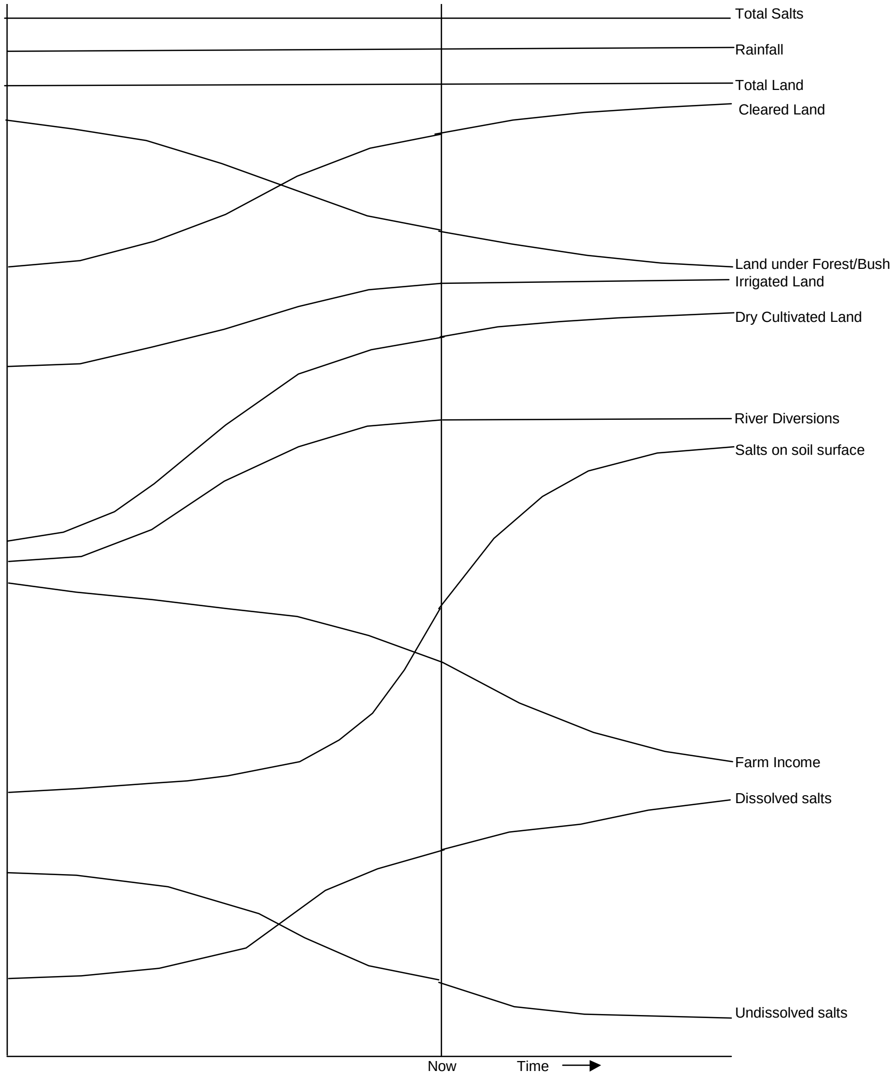


Figure 7. A Reference Mode for Salinity Problem (Khan, McLucas et al. 2004)

3.5 CAUSAL LOOP DIAGRAMS

In a dryland salinity system, the land is considered under different covers/uses. The primary land cover is natural vegetation. Based on the demand for land clearing, the land under natural vegetation is cleared if it is available for clearing. Higher rates of land clearing reduce the total land under natural vegetation. Figure 8, shows this relationship. Land is cleared according to a Land Clearing Discrepancy (LCD). As the LCD increases, more land is cleared subject to its availability. LCD is a difference between the demand for cleared land

and already cleared land. The demand is considered exogenous to the model as it may vary depending upon multiple factors like the conditions of the external global market, commodity prices, political objectives of the government, e.g., settlement in a certain areas. Land clearing operations depending upon their time-lags convert land cover/use from a naturally vegetated land to cleared land available for multiple uses.

Land clearing reduces the evapotranspiration and increases the ground recharge. This increased recharge, along-with the groundwater movement and depending upon groundwater response times, adds to the ground water at different areas and moves the watertable close to the land surface. A rise in water table may dissolve salts in the different soil layer and may cause land to become either salt affected or at the risk of becoming salt affected (when the water table reaches within 2 meters of the land surface). The relationship between natural vegetation and the hydrological cycle is depicted in the following excerpt:

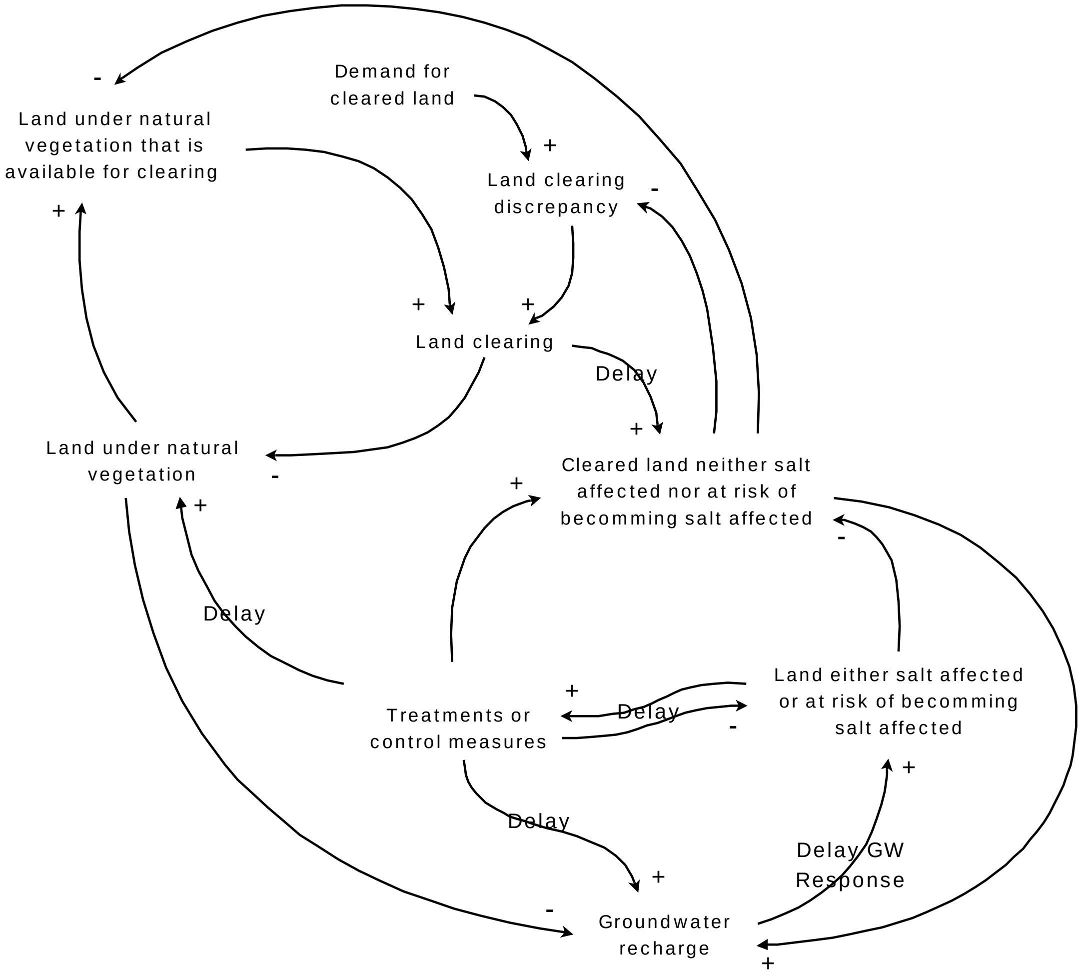


Figure 8. Causal loop diagram of the dryland salinity problem in Australia.

The native vegetation regimes evolved to make the best use of available rainfall while avoiding the salts. All vegetation pumps water from the soils and transpire a component to the atmosphere (through the evapo-transpiration process). Any change in vegetation density or type (e.g., a change in vegetation's water pumping capabilities) will alter the volume of *water reaching the saturated zone below. Clearing of native vegetation disturbed the current balance." (Evans, Newman et al. 1996)*

After a certain time-lag, the impacts land clearing start to emerge, and the decision makes within implement treatments or control measures to combat dryland salinity. These treatments after a delay, depending upon their effectiveness, help to lower down watertables either by improving the landcover or through their water utilization (root/shoot characteristics). In this way the entire system locks itself into land degradation from land under natural vegetation into the land that is either salt affected or at the risk of becoming salt affected. Overtime as the land availability for clearing becomes, less and less the rates of land clearing decreases.

Time delays are of crucial importance in understanding time dynamics and impacts of land-use change. Groundwater systems respond to a land clearing option over a long time. Figure 9 shows of time delays in the groundwater response. The figure indicates that the response of groundwater to an intervention is slow in the local groundwater systems and may take around 30 years to complete response. In the medium ground water systems the full response to an intervention like land clearing is around 200 years the regional groundwater flow systems may give only 20 percent response in the 200 years.

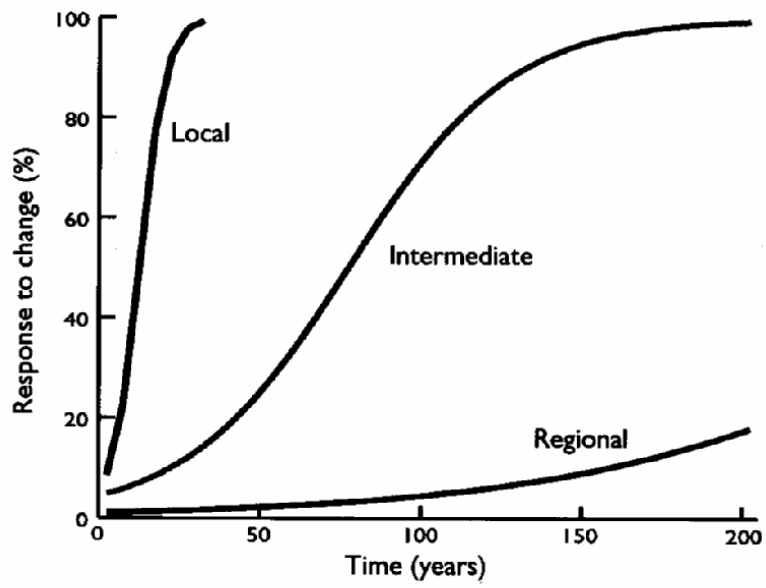


Figure 9. Time response characteristics of ground water flow systems (NLWRA 2000)

3.6 A SIMPLE SIMULATION MODEL

A simple model was developed in the Powersim Studio 2003. During, the process of a simulation model development, the systems engineering 'Vee diagram' (Figure 10) was used as a guide. The Vee model consists of lists of steps that a modeller follows to streamline the model development process. It provides an opportunity to explicitly engage the modeller in the process of decomposition and definition of the model requirements including detailed plans for module specifications. Then, the process leads to integration and verification of the model.

To accomplish this purpose, a modular approach was used. Each module was developed and validated in terms of mass balances, sensitivities, dimensional consistency and boundary adequacy. Then the modules were connected to develop into the main model.

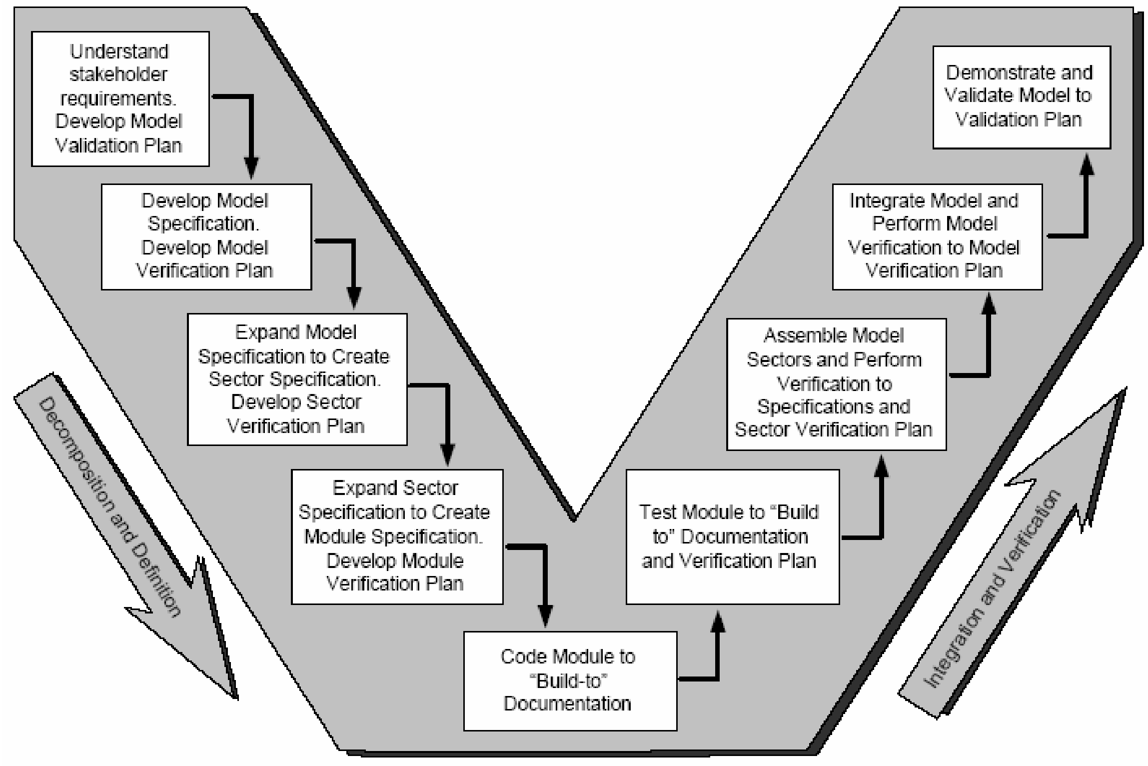


Figure 10. Vee Diagram of systems Engineering (Mclucas and Ryan 2005)

3.6.1 Model Purpose and Performance Requirements

The purpose of this modelling effort is to develop a simple model that helps to understand the impacts of delays on different land categories directly linked to the dryland salinity problem. However, the model does not intend to predict the quantity of actual salt affected lands or the quantity of salt at a certain geographical location. The model should incorporate some of the variables identified in the causal loop diagram. The model should be concise and simple enough to be used for communication purposes and it should provide a user interface to allow users the change the inputs. The model should exhibit past behaviour close to the one identified in the reference modes (Figure 7).

3.6.2 Stocks and Flows in the Systems

A simple model (Figure 12) depicts these interactions by three stocks:

- Land under natural vegetation.
- Cleared land neither salt affected nor at risk of becoming salt affected.
- Cleared land either salt affected or at the risk of becoming salt affected: A piece of land is considered at risk of becoming salt affected if it has the watertable within 2 meters beneath the surface.

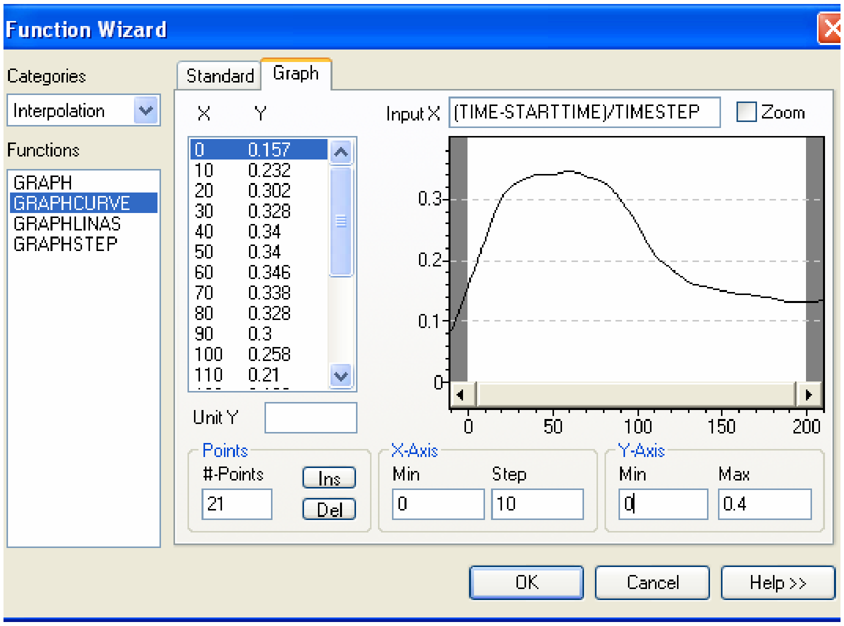
The initial values of the stocks are user controlled and provide a room for experimentation. Initial values of stocks have two components: total area of the Basin and the fraction of that area pertaining to that particular stock.

These stocks are linked by four flows:

- Rate of land clearing.
- Rate of land becoming salt affected.
- Rate of land reclamation.
- Rate of land either salt affected or at the risk of becoming salt affected returning to natural vegetation.

The time delay in land clearing is a user defined variable and includes the time that is consumed in planning, land acquisition, getting permissions for land clearing, arrangements for the machinery, acquisition and movement of machinery and felling and export of logs from the area. As there may be varying time for different areas, land clearing operations, communities. To check sensitivities, a random variable is used.

The fraction of land under natural vegetation that is being cleared is considered to be varying overtime. The input data is given through the following graph (Figure 11). The maximum rate is considered between 30-35% during the middle of the last century. Under the current environmental pressures and data provided by the Australia Greenhouse Office (AGO 2000), it was considered that during later part of the last century, land clearing rates were stated to decline.



Categories: Interpolation

Functions: GRAPHCURVE

Input X: (TIME-STARTTIME)/TIMESTEP

☐ Zoom

X	Y
0	0.157
10	0.232
20	0.302
30	0.328
40	0.34
50	0.34
60	0.346
70	0.338
80	0.328
90	0.3
100	0.258
110	0.21

Points: #-Points 21

X-Axis Min 0
X-Axis Step 10

Y-Axis Min 0
Y-Axis Max 0.4

Figure 11. changes over time in the fraction of land being cleared.

Fractions of a land not at risk of becoming salt affected to become at risk, is defined as a random variable. This fraction also depends upon multiple factors like growth of returns from an agricultural land, high yielding cultivars and mechanical operations. This variable is described by using the graph shown in the Figure 13.

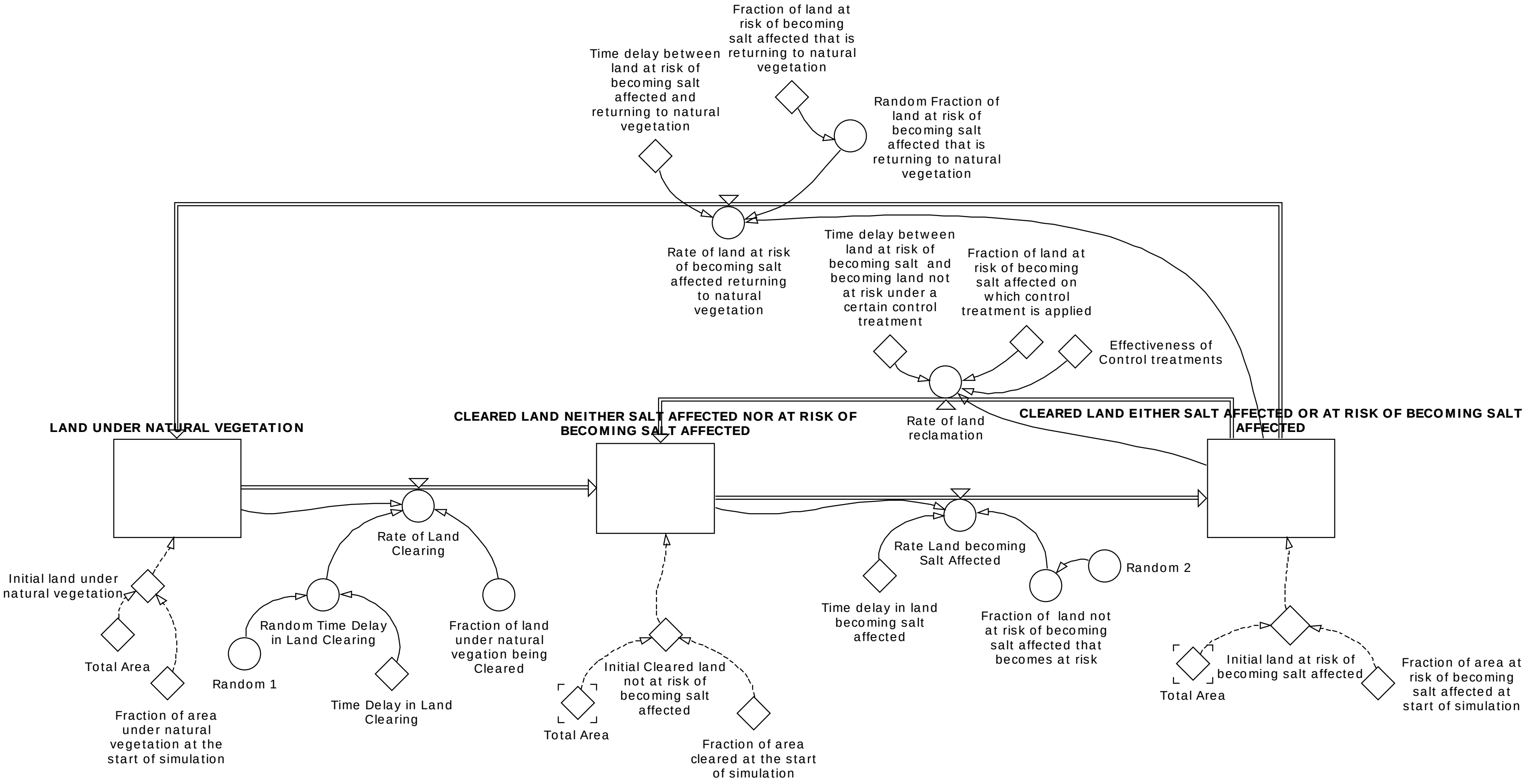
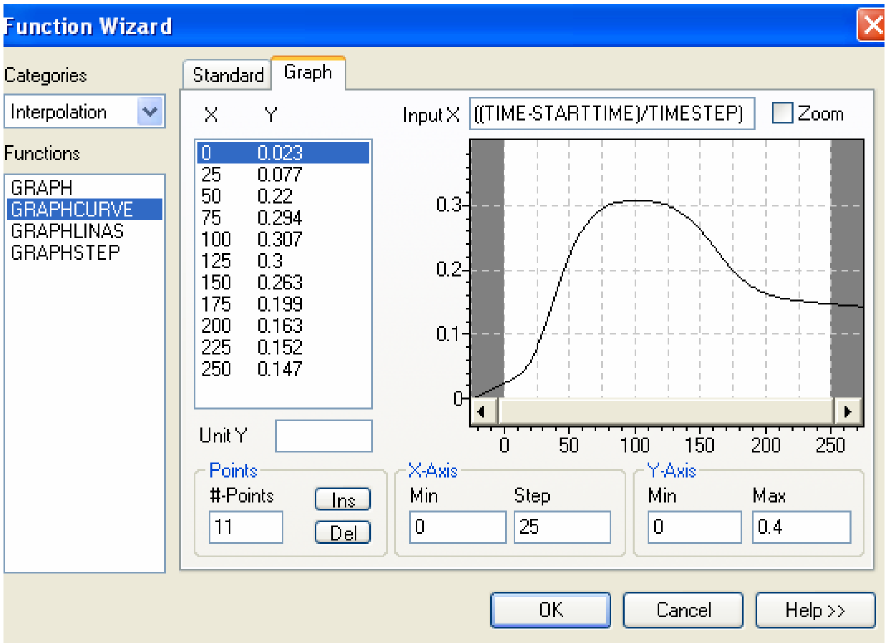


Figure 12. Stock and Flow Diagram of the Dryland Salinity Model



Categories: Interpolation

Input X: ((TIME-STARTTIME)/TIMESTEP) ☐ Zoom

X	Y
0	0.023
25	0.077
50	0.22
75	0.294
100	0.307
125	0.3
150	0.263
175	0.199
200	0.163
225	0.152
250	0.147

Unit Y:

Points: #-Points 11

X-Axis Min 0 Step 25

Y-Axis Min 0 Max 0.4

Figure 13. Fraction of non-saline land becoming salt affected.

3.6.3 Simulation Results and Discussion

The simulation was run over a 200 years period from 1900 to 2100, keeping in view the long response times of groundwater flow systems, operations involved in clearing, and long delays between the establishment of the control measures and the time when these become effective.

The model exhibits the behaviour shown in the Figure 15 when given the default values (Figure 14). Figure 15 indicates that the land under natural vegetation decreases and starts to stabilize in the last decades of the last century. One reason for this decrease is the large scale land clearing for agricultural uses as documented in the Section 3.3 and Figure 4. The causes for the stabilization after 1980 are two fold. First, the extensive land clearing in the first half of the century reduced the land that is available for clearing and reduced the rate of increase in land clearing. Secondly, the impacts of land clearing started to be realised and the Commonwealth and State Governments undertook steps to discourage land clearing. The behaviour is close to the reference modes depicted in the Figure 7.

With the decrease in natural vegetation, cleared land that is neither salt affected nor at the risk of becoming salt affected (Figure 15, blue curve) increases. After a certain time delay, the cleared land started to become salt affected (Figure 15, red curve) near 1950s and steadily increases until 2050, after which, it starts to stabilize until 2100. The increase in cleared land from 1900 to 1950 was because the more land becoming cleared as a result of increase in demand for land clearing. Around 1950s, as the cleared land became salt affected or at the risk of becoming salt affected, the inventory of cleared land decreased. Between 2000 to 2100, the cleared land is likely to be influenced by two factors: a decrease in the rates of land clearing and an increase in the rates of salinization. This caused a decreased in the cleared land stock. This relationship is depicted by the reference modes showing the cleared land and land under forest in the Figure 7.

Initial Values: these are the values of the stocks that are used at the start of simulation period

Total Area

Fraction of area under natural vegetation at the start of simulation

Fraction of area cleared at the start of simulation

Fraction of area at risk of becoming salt affected at start of simulation

Land fraction: this is fraction of a certain category of land

Fraction of land at risk of becoming salt affected that is returning to natural vegetation

Fraction of land at risk of becoming salt affected on which control treatment is applied

Time Delays: this is time consumed in a process or change of state

Time Delay in Land Clearing

Time Delay between non saline land becoming salt affected

Time delay in land becoming salt affected

Time delay between land at risk of becoming salt and becoming land not at risk under a certain control treatment

Time delay between land at risk of becoming salt affected and returning to natural vegetation

Effectiveness of Control Treatment

Effectiveness of Control treatments

Figure 14. Default Values in the Control Panel of the Model.

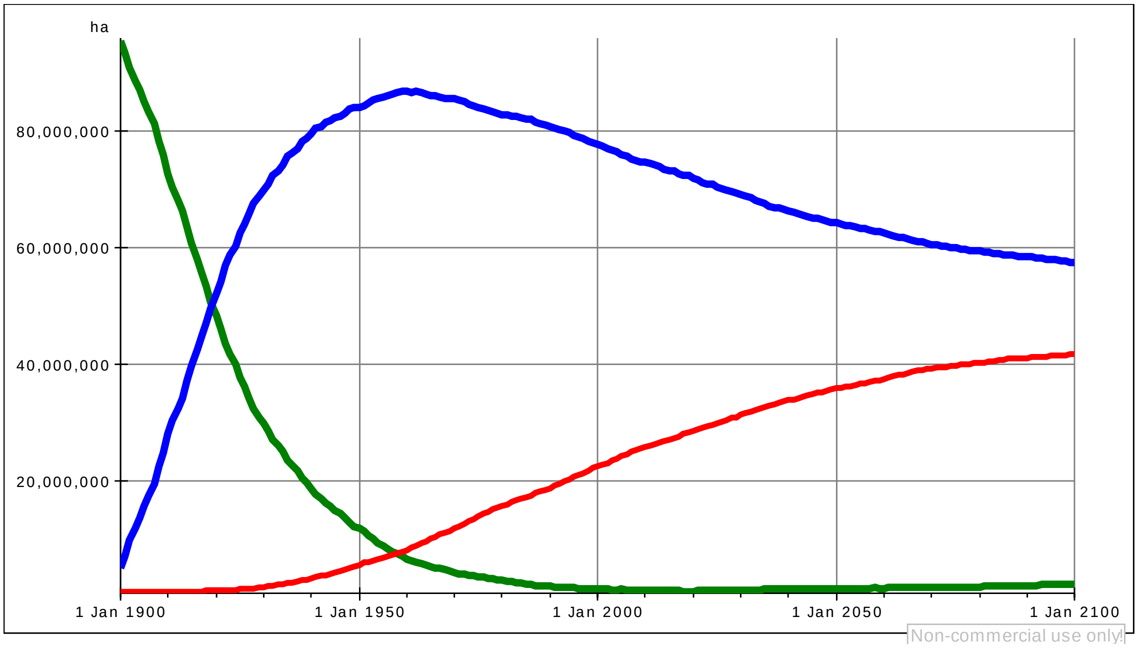


Figure 15. Behaviour of stocks in the Dryland Salinity Model. Green curves indicate the land under natural vegetation while, the Blue curve indicates the cleared land neither salt affected nor at the risk of becoming salt affected while the Red curve indicates the land either salt affected or at the risk of becoming salt affected.

The inferred behaviour of dryland salinity problem can also be explained using ‘Limits to Growth’ systems archetype. Along-with other factors, lack of availability of land for clearing is itself becoming a controlling factor. The expansion of agriculture in 1900 by converting natural forest land into farms helped the growth of agricultural sector. As land availability started to reach its limits, the impacts of growth (e.g., dryland salinity), themselves, started to control the growth. This also provides an explanation for the farmers worsening terms of trade and negative impacts on farm incomes as depicted in the Figure 6.

The model so developed can act as a learning tool. It provides input controls that a user can change, conduct experiments with the model and observe the impacts of those changes.
Figure 16 shows results of such experimentation. The experiment was conducted using the model to observe the effects of salinity control measures. The control measures (Plant/crop based) appeared to have a positive impact on the land at the risk of becoming salt affected. An increase from 0.1 to 0.8 and change in fraction of the area on which control treatments are applied from 0.1 to 0.3 in effectiveness of control measures, the model indicated that the increasing trend of the land at the risk of becoming salt affected (Figure 16 red curve) can be stabilised and can start to decrease near the last quarter of this century. This is because the control measures based on their different recharge potential can decrease recharge to the groundwater, as depicted in the causal loop diagram (Figure 8). Further experiments can be done with different levels of effectiveness of the control measures.

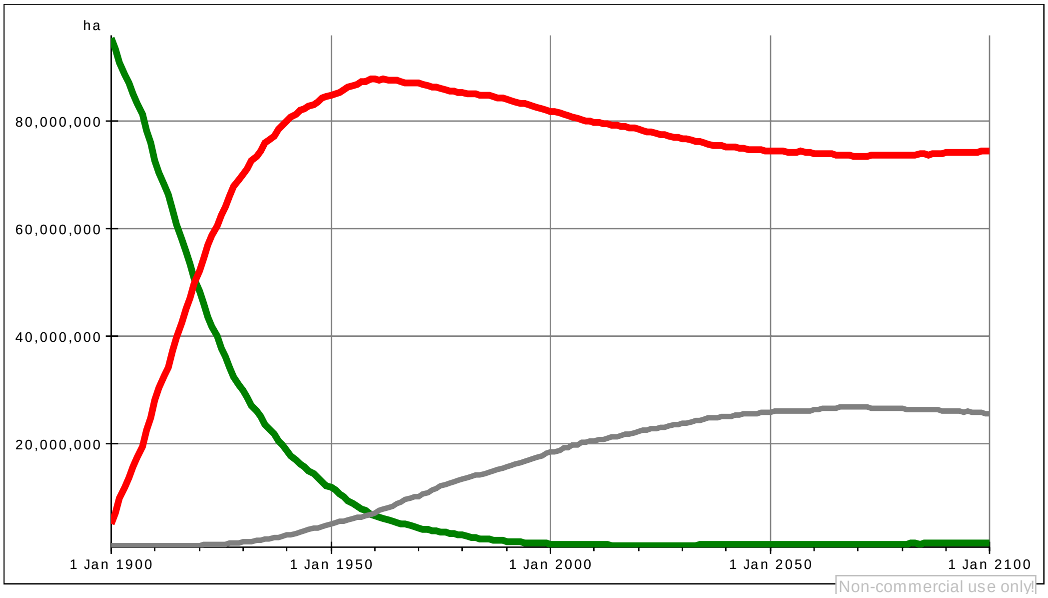


Figure 16. Effects of control measures/ treatments on the land either salt affected or at the risk of becoming salt affected.

3.7 SUMMARY AND CONCLUSION:

This paper described a structured approach to develop a system dynamics model for dryland salinity problem that started with problem description from a systems perspective, used learning cycles approach for development of reference modes, developed causal loop diagrams to aid analysis and then employed a systems engineering approach to streamline the simulation model development process. By doing so, this paper demonstrated how such approaches can be used conjunctively to aid analysis of the complex problems using a case study of the dryland salinity in the Murray Darling Basin.

Over the last 200 years, Australia has improved its agricultural production by converting natural vegetated land into agricultural farms, increased water diversions from rivers. This has caused some unintended consequences. Dryland salinity is one of such unintended consequences. This occurred because there are long time delays in response of different groundwater flow systems and from initiation of control measures/treatments to their maturity. The delays implied in response of the groundwater flow systems indicates that the some of the impacts of the land clearing done in early 1900s are yet to occur.

The model can be used can be calibrated and used in other regions where broad policy measures are to be identified to identify the strategies that respond to natural time delays involved in the dryland salinization processes. The model can also be used to evaluate the effectiveness of treatments or control measures. The model itself can be further developed and used for the study of effects of delays in groundwater response, natural land recovery, reclamation efforts on the respective stocks. The model can also provide a tool for communicating these impacts between policy groups and farming communities at strategic levels.

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