# A Case Study in Application of Vee Model of Systems Engineering to System Dynamics Modelling of Dryland Salinity in Australia

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**ABSTRACT**

*This paper describes an application of the Vee Model of Systems Engineering in developing a System Dynamics model of dryland salinity in the Murray Darling Basin. A modular approach was adopted. Simple modules of salt affected land were developed using Powersim Studio following decomposition, definition, integration and verification processes. Individual modules were verified, integrated and provided with options for policy testing. The use of Vee Model provides a structured way for developing computer simulation model with a top-down approach for requirements elicitation and ensures that the computer model meets requirements and limitations elicited through qualitative System Dynamics and defined at the start of the modelling exercise. It also provides rigorous verification processes. The results of this research provide an avenue for further exploration of the synergistic use of the two approaches to improve model quality.*

**Key Words: System Dynamics, Systems Engineering, Vee Model, Dryland Salinity, Australia**.

## 1 INTRODUCTION

The purpose of a System Dynamics inquiry is to improve our understanding in and about complex systems. The goal of modelling is to improve understanding of the relationships between feedback structure and dynamic behaviour of a system, so that policies for improving the problematic behaviour may be developed (Richardson 1981). This purpose is achieved through development of qualitative as well as computer simulation models.

Development of computer simulation model poses a special challenge to a modeller as the qualitative models like causal loop diagrams, concept maps, systems diagrams carry a rich picture of the problem to be modelled. The computer simulation, however, may not include all those variables due to what Coyle (1999; 2000) calls limits to quantification.

Richardson (2001) and Homer and Oliva (2001) suggest that simulation nearly always adds value to policy analysis, even in the face of significant uncertainties and soft variables. Sterman (2000) highlights the need for quantitative models as our mental models are dynamically deficient, that is, they omit feedbacks and time delays, accumulations and non-linearity with the consequence that simulation is the only practical way of testing our mental models, noting that the complexity of our mental models vastly exceeds our capacity to understand their implications.

Systems Engineering has a strong tradition in complex project management and provides an opportunity for development of simulation models through a structured process. McLucas and Ryan (2005) highlight the strengths of Systems Engineering in design, building and testing quantitative System Dynamics models including the detailed transition from conceptual representation to quantified model. They examined the System Dynamics modelling process and suggested the following benefits by using the Systems Engineering process:

- deliberate and careful management of the complexity introduced at each stage of the model building process;
- discipline and rigour associated with requirements engineering;
- aid in managing and coping with complexity through a top down approach; and
- rigour in validation and verification.

This paper describes founding research on application of Vee Model of Systems Engineering to development of a simple System Dynamics model of dryland salinity in the Murray Darling Basin, Australia. First, Vee Model is described that is followed by the description of the activities undertaken at each step of model development and resultant models.

## 2 VEE MODEL OF SYSTEMS ENGINEERING

Sage (2005) defined Systems Engineering as a process that is comprised of a number of activities that will assist in definition of requirements for a system, transform this set of requirements into a system through development efforts and provide for deployment of the system in an operational environment.

System Engineering uses a distinct system development process. This process coincides with a systems lifecycle and lists key steps in the system development from concept to development, integration, testing and deployment of the system. This process is usually represented in a diagram that is in the shape of English letter “V” and is also called as a “Vee Model”. A traditional Vee is based on project cycle and represents a progressive product development process.

Forsberg and Mooz et al. (2005) presented a Vee Model addressing architecture decomposition, integration and verification. The model presents both system development planning and system realization activities. Forsberg and Mooz et al. (2005) also presented detailed Vee models for decomposition, integration and verification. Figure 1 shows a high level Vee Model that presents decomposition and definition on the first leg and integration and verification on the second leg of Vee Model. Thickness of the Vee increases near bottom of the Vee and indicates the increasing number of activities at that level.

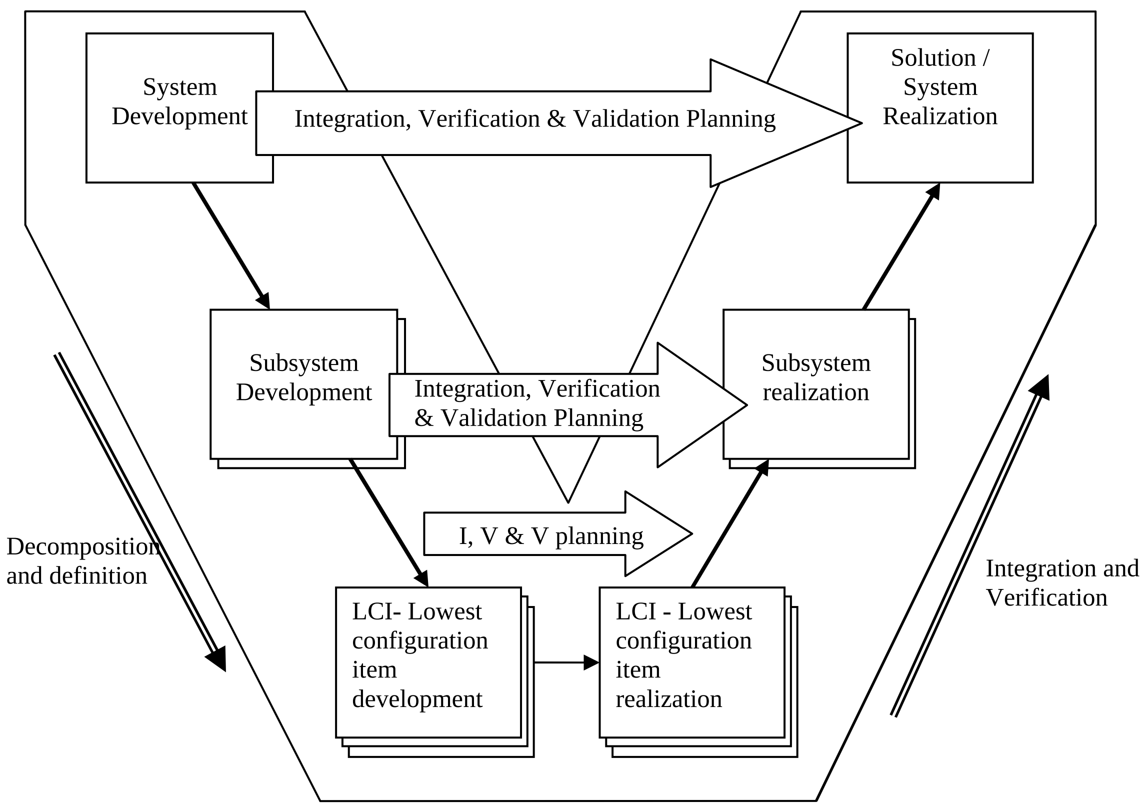


**Figure 1 Vee Model of Systems Engineering re-drawn from Forsberg, Mooz et al. (2005)**

Lead authors in Systems Engineering have used multiple variants of the Vee Model. Despite variations, Vee Models present similar activities though with different terminology and the use of various levels of decomposition and integration. The first leg of the Vee Mode shows the activities involved in planning for the development of a system, e.g., concept, requirements or expectations form the system and design. A system is first decomposed to identify requirements. Components are designed and then integrated to progressively prove performance and compatibility of all components of the system.

In Systems Engineering process, verification is used to ensure a product or system is built according to its specifications while validation is the user satisfaction regardless of specifications. Forsberg and Mooz et al. (2005)'s Vee Model shows that integration, verification and validation activities are planned at the system decomposition level when the subsystems, modules and lowest configuration items (LCIs) are developed.

Neudorff, Randall et al. (2003) presented a different Vee Model with multiple levels in decomposition and integration, for example, they further divided requirements and design into high level and detailed requirements and high level and detailed design. The first leg his Vee Model addresses concept of operation, requirements, design, implementation, integration and testing, subsystem verification, system acceptance and operation and maintenance.

For this paper, a general approach to Vee Model presented by Forsberg and Mooz et al. (2005) is adopted. Key activities of the System Dynamics modelling process are grouped and represented according to this Vee model.

For this study, a System Dynamics model for the dryland salinity was considered as a system to be developed. The knowledge gained through qualitative modelling process, e.g., learning cycles, reference modes and concept mapping constitutes the baseline requirements for model development and informs the decomposition and definition for identification of modules. Table 1 shows the Systems Dynamics modelling activities used for this study against Vee Model.

**Table1: System Dynamics Modelling activities organized according to Vee Model of Systems Engineering.**

<table>
<tr><th colspan="2">Vee Model Components</th><th>System Dynamics Modelling activities</th></tr>
<tr><td rowspan="3">Architecture - Decomposition and Definition</td><td>System level decomposition-<br><br>Concept of operation<br>Requirements Elicitation</td><td>Qualitative System Dynamics:<br>- Learning cycles<br>- Reference modes<br>-Concept maps<br>-Systems arch-types analysis<br>- Causal loop diagrams</td></tr>
<tr><td>Subsystem level decomposition<br>Development of specifications.<br><br>Planning for integration, verification and validation of subsystems.</td><td>- Identification of stocks and flows.<br>Identification of the individual modules needed to represent the problem.<br>- Stock and Flow Diagrams.</td></tr>
<tr><td>LCI- Lowest configuration items development</td><td>Identification of Auxiliaries, constants.</td></tr>
<tr><td rowspan="4">Architecture - integration, verification and validation</td><td>System realization.</td><td>Integration of individual modules into a whole model including interfaces, policy levers, input controls, output objects, data transfer facilities etc.</td></tr>
<tr><td>Subsystem realization.</td><td>- Built-up of individual modules with stocks, flows, auxiliaries, constants using a system dynamics modelling software, e.g., Powersim Studio<br>- Development of interfaces and model input controls, e.g, slider bars, switches, gauges etc.<br>- Development of the output objects, e.g., graphs, tables, gauges,<br>- Development of individual modules</td></tr>
<tr><td>LCI Solution system realization.</td><td>Development of individual rate models with auxiliaries and constants.</td></tr>
<tr><td>Compliance to baseline verification & validation.</td><td>- Examination of each equation to verify that it represents real world counterparts and follows the model logic.<br>- Model validation tests.</td></tr>
</table>

# 3 DRYLAND SALINITY IN AUSTRALIA: A SNAPSHOT OF THE PROBLEM

A detailed description of the dryland salinity was presented in System Dynamics Society Conference 2006 (Khan, McLucas et al. 2004; Khan and McLucas 2006). As the focus of this paper is on demonstrating Systems Engineering approach, therefore, detailed description of dryland salinity is not given to accommodate the detailed description of the ways in which Systems Engineering was applied. Here brief conclusions about the problem from earlier papers (Khan, McLucas et al. 2004; Khan and McLucas 2006) are reproduced.

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. The problem has developed over a long time as a result of the feedback interactions among various climatic, geographic, environmental and human factors.

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 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.

# 4 DECOMPOSITION AND DEFINITION (THE FIRST LEG OF VEE MODEL)

Decomposition refers to further break down of a perceived system into manageable components. During decomposition and definition, a system is partitioned into hardware, software components and operator activities and each component is then designed, built and coded according to its functional and physical content (Forsberg, Mooz et al. (2005:110). Requirements of a system (system dynamics computer simulation model in this case) are elicited through multiple methods (mentioned in the column three of the Table 1), analyzed and subsequently converted into specifications of the system to be developed.

## 4.1 **REQUIREMENTS ELICITATION**

A qualitative analysis of the problem was undertaken and reference modes of the problem, concept maps and causal loop diagrams were prepared. The Reference modes and causal loop diagrams were presented at the System Dynamics Society Conferences in 2004 and 2006 (Khan, McLucas et al. 2004; Khan and McLucas 2006) respectively. Detail about qualitative analysis is not presented here due to limitations on scope of the paper. This qualitative analysis provided requirements for the model in terms of model purpose, performance expectations and module specifications that are describes in the following paragraphs.

## 4.2 **MODEL PURPOSE, SCOPE AND INTENDED USES**

The main purpose was to develop a simple model that helps to understand the impacts of land clearing and time delays on different land categories undergoing dryland salinity in Australia. 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 be concise and simple enough to be used for communication purposes and it should provide a user interface to allow users to change the inputs. The model should exhibit past behaviour close to the one identified in the reference modes. As the reference modes were prepared using descriptive data, the model output is not expected to provide statistical correlation.

The model provides an opportunity for understanding causal mechanisms underlying the perceived system, and it should not be used as a framework for statistically based inferences.

The qualitative analysis in the form of causal-loop diagrams, concept maps and the reference modes presented the qualitative analysis of the dryland salinity problem. The qualitative analysis presented a large number of variables that are important in understanding this problem. The simulation model takes few key variables related to the land cover as related to the dryland salinity.

The model must conform to the following expectation:

- The model should address land clearing issue as related to dryland salinity and help develop a strategic view of the problem.

- Model should help in understanding the impacts of time delays on different land progressing through different stages.
- The model should aid learning about the impacts of land component of the dryland salinity problem.
- The model should provide policy levers for experimentation.
- The model is to be used as a research tool to investigate synergies between System Dynamics and Systems Engineering for model development.
- The modelling should be started simple. However, the model should have flexibility to allow additional detail/modules to be added, as needed to aid analysis and subsequent learning.
- Model should use the important variables that can directly influence dryland salinity.
- The model should address the timeframe and model boundary requirements elicited through qualitative System Dynamics.

## 4.3 **MODEL SPECIFICATIONS**

The simulation model consists of land cover sector. However, the model has flexibility for other sectors for example population and socio-economic sectors to be added in future research. The model provides a framework for learning about the impacts of time delays, different land clearing rates, and application area and effectiveness of control treatments over dryland salinity in the Murray Darling Basin.

A simple model 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 consistent with the NLWRA (2001).

The initial values of the stocks are user controlled and provide a room for experimentation. 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.

# 5 MODEL REALIZATION: DEVELOPMENT, INTEGRATION AND VERIFICATION (THE SECOND LEG OF VEE MODEL)

## 5.1 DEVELOPMENT OF INDIVIDUAL MODULES.

The individual module structure was developed using a generic module specified by McLucas (2003) and defined by its boundary and functionality. According to McLucas (2003) the functionality of a module means the operations it performs on the inputs, e.g., accumulating, draining, etc. The outputs from a module are either lost across a boundary or made available to another module.

The generic model consists of one stock and two flows. One flow is into the stock and accumulates stock and the other is out of the stock and drains it. Flows and their determinants are within a module boundary. Across the boundary, there are physical and information flows as well as datasets that provide it connectivity to other modules and its environment. The generic module is shown in the Figure 2.

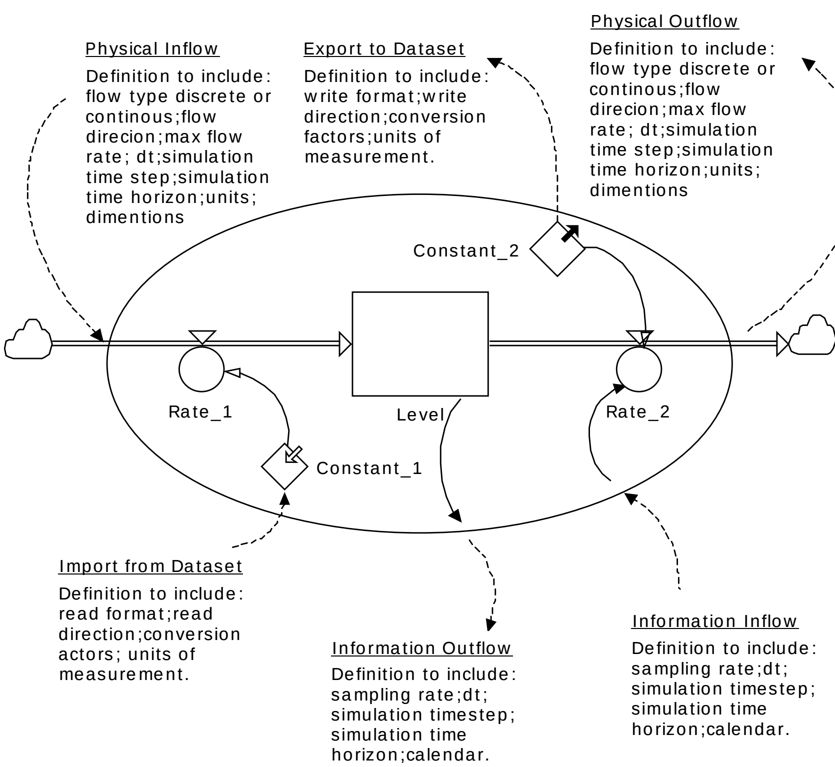


**Figure 2 Structure of a generic module. Redrawn from McLucas (2005:179)**

## 5.2 STOCKS AND FLOWS

The model presents a simple three land stocks, i.e., land under natural vegetation, cleared land neither salt affected nor at the risk of becoming salt affected, and land either salt affected or at the risk of becoming salt affected. These stocks are linked by four flows, i.e, 'rate of land clearing', rate of land becoming salt affected', 'rate of land reclamation and the rate of land at risk of becoming salt affected that is returning to a natural vegetation cover. For developing modules, a modular approach was adopted that encourages starting simple and then adding details as necessary.

### 5.2.1 Land Stock 1: Land under natural vegetation.

The stock 'Land under natural vegetation' represents land either bush or forest that has not been cleared for agricultural purposes under land clearing operations. This stock is represented in the model diagram by a rectangle. Land clearing rate drains it while rate of land becoming salt affected returning to natural vegetation adds to this stock. This simple formulation is represented in the Figure 3. A negative feedback loop manages the level stock. As the rate increases of land clearing increases, it decreases the stock of land under natural vegetation.

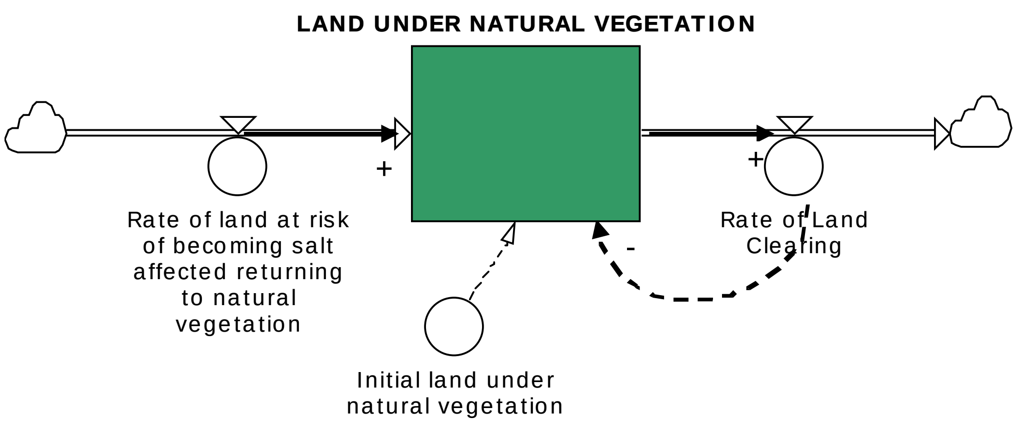


**Figure 3 'Sub-model land under natural vegetation**

### 5.2.2 Stock 2: Cleared land neither salt affected nor at risk of becoming salt affected.

Cleared land represents a piece of land that was previously under natural vegetation either bush or forest and is cleared for the purposes of bringing it under agricultural production. Two rates 'Rate of land clearing' and cleared land neither salt-affected nor at risk of becoming salt-affected' compound this stock while the rate 'Rate of land becoming salt affected drains it. There is a negative feedback loop that manages this stock. The rate reduces the stock (shown in dashed lines) and low stock causes a reduced rate of land becoming salt affected' as rate equation is formulated as a fraction of the stock. Rate formulations are discussed in the following sections. The inflows and outflows of this stock are presented in the 4.

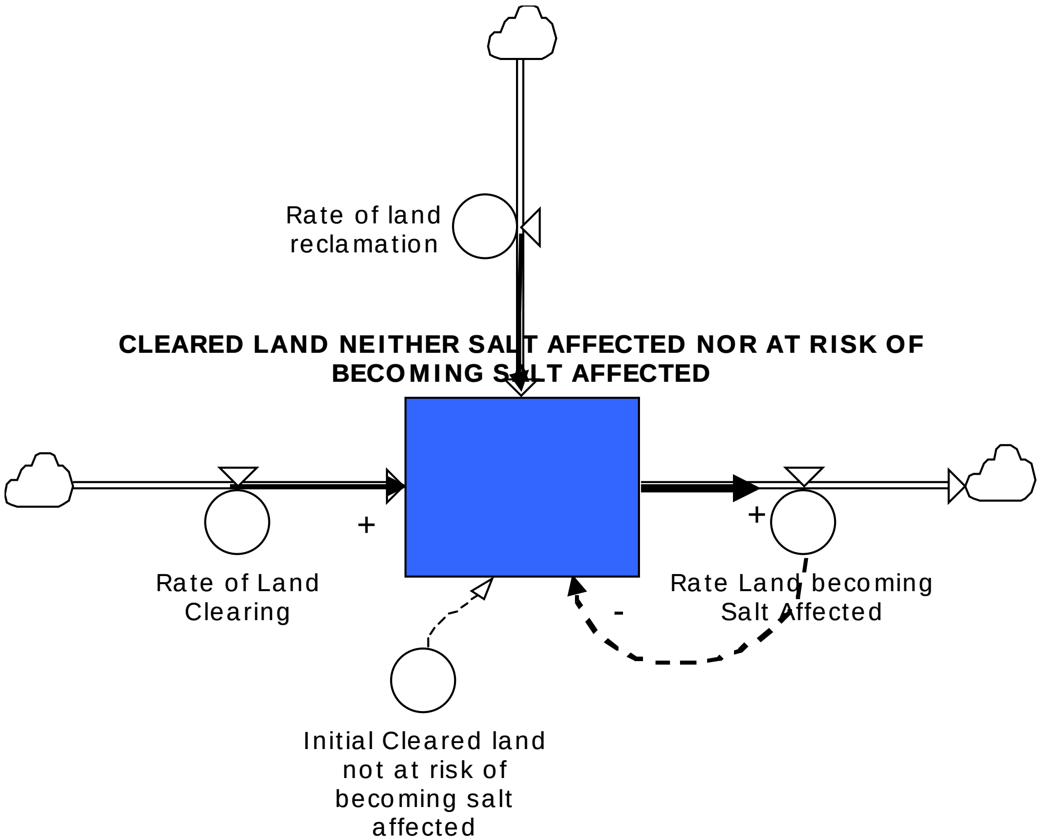


**Figure 4 Sub-model cleared land neither salt affected nor at the risk of becoming salt affected.**

### 5.2.3 Land stock 3: Cleared land either salt affected or at the risk of becoming salt affected.

As it is clear from the stock name, this stock represents pieces of land that is already salt affected or is at the risk of becoming salt affected, i.e., watertable is at or within 2 meters from the ground surface. This stock has one inflow that compound the stock and two outflow that drain this stock. A simple representation of the stock is presented in the Figure 5. The inflow is 'Rate of land becoming salt affected'.

There are two outflows, i e., 'Rate of land at risk of becoming salt affected returning to natural vegetation' and the rate of land reclamation. There are two negative feedback loops that manage this stock (shown with broken lines in the Figure 5).

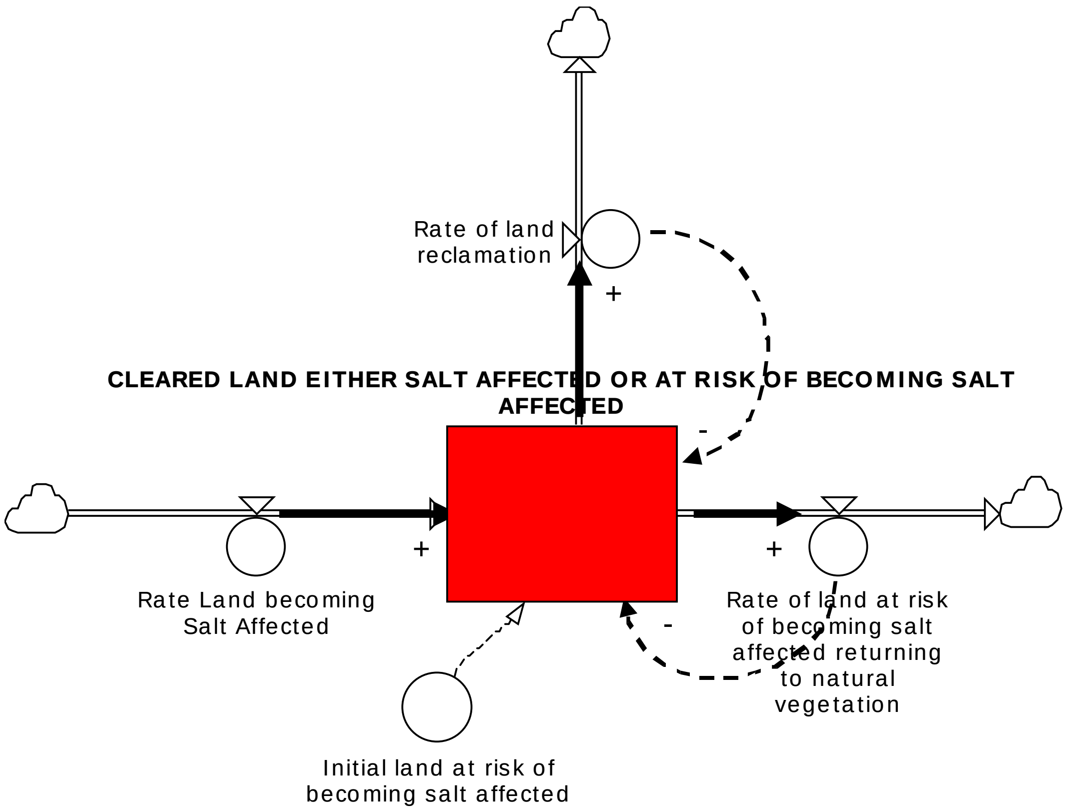


**Figure 5 Sub-model land either salt affected or at the risk of becoming salt affected.**

### 5.2.4 Rate of Land Clearing

A sub-model providing land clearing rate is shown in the Figure 6. For this sub-model, rate of and clearing is defined as a fraction of the land under natural vegetation.

Rate of land clearing = Land under natural vegetation * Fraction of land under natural vegetation./Time delay in land clearing

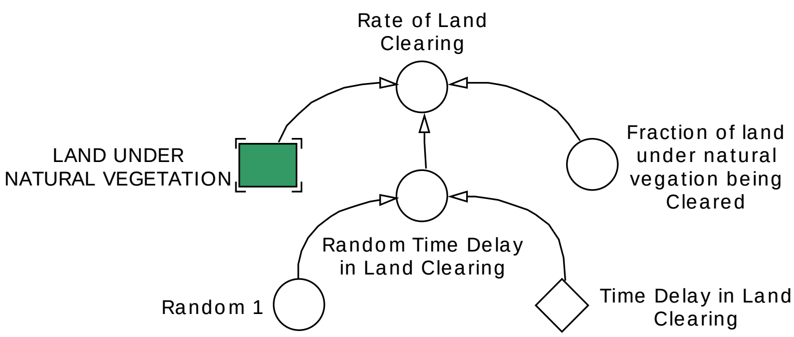


**Figure 6 Rate of land clearing**

Fraction of land under natural vegetation being cleared is modelled on the basis of the historical data of land clearing developed from different references. The fraction of land under natural vegetation that is being cleared is considered to be varying overtime. The input data is given through a graph. 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 started to decline.

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.

Time delay in land clearing provides for the time spent in planning for land clearing, getting approvals/permissions, accessibility to the area and finally clearing the land of its natural vegetation either bush or forest. Time delay is a user controlled parameter. Default value is 10 years. As the actual time delay will vary over simulation period, therefore, a random number has been used that fluctuates between 6 and 10 years.

Random 1 = Random (0.5, 1.0, 0.9)

### 5.2.5 Rate of land becoming salt-affected

Rate of land becoming salt affected is depicted in the Figure 7 and is defied as:

Rate of land becoming salt affected = Cleared land neither salt affected nor at the risk of becoming salt affected*Fraction of land not at the risk of becoming salt affected

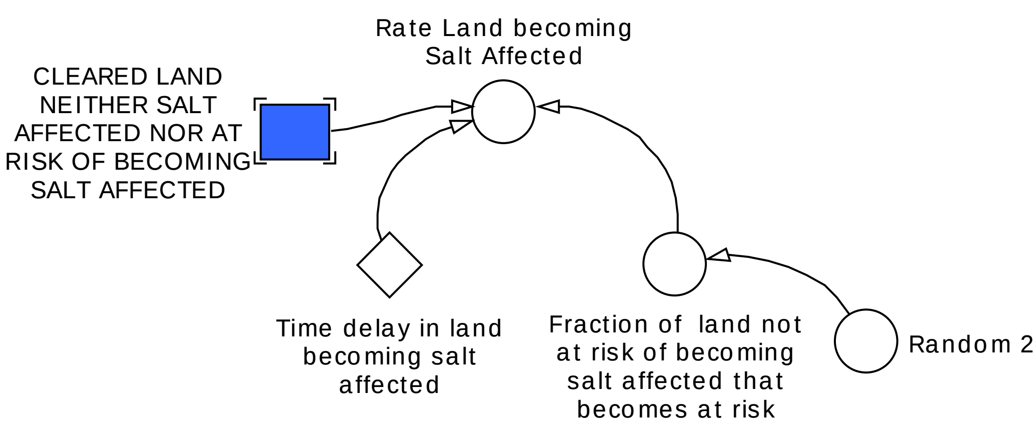


**Figure 7 Rate of land becoming salt affected**

Fraction of cleared land that becomes salt affected is provided by historical evidence developed in the process of developing reference modes. The fraction near negligible at the start of the simulation, reaches a peak around 0.3 around 2000 and reduces to 0.1 near the end of simulation period. As accurate estimates of the rates could not be obtained, a random number given below fluctuates the fraction around the points in the table function.

Random 2 = Random (0.5,1.0, 0.9)

Time delay in a land becoming salt affected or at the risk of becoming salt affected is not actually known. It would vary according land policies, specific geo-physical and social set-up and market forces. Time delay in land becoming salt affected is a user controlled parameter. The default value is rough estimate of 30 to 40 years. A random variable (Random (0, 1, 0.5)) fluctuates this time delay between 0 and 40 years over the simulation period.

### 5.2.6 Rate of land reclamation

In this model, the rate of reclamation has been defined as function of the fraction of land either salt affected or at the risk of becoming salt affected on which a control treatment is applied, time delay and effectiveness of the control treatments. The model that provides the rate of land becoming salt affected is shown in the Figure 8.

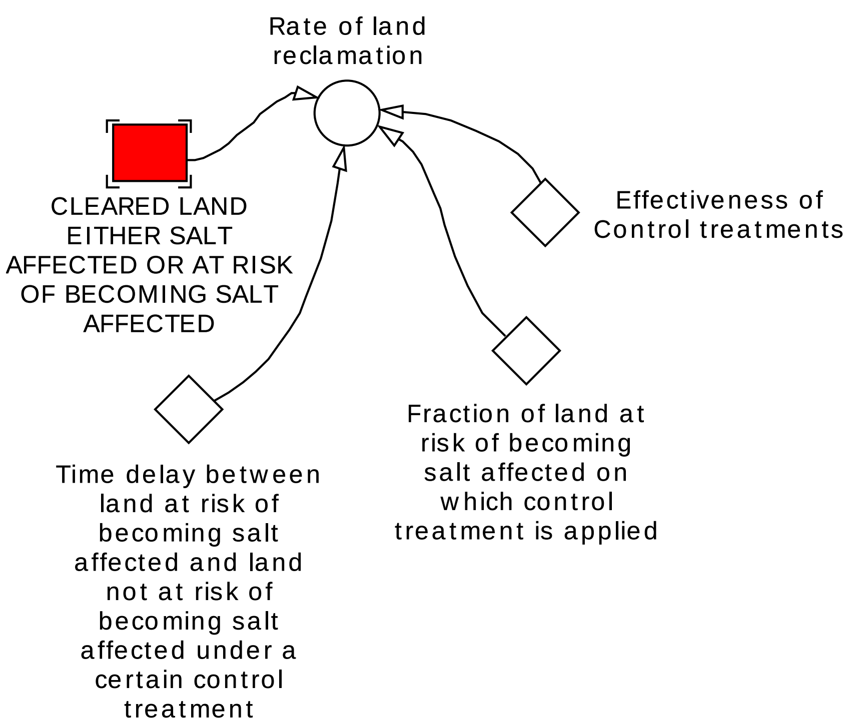


**Figure 8 Rate of land reclamation**

For simplicity, a single category of salt affected land or land at risk of becoming salt affected. However it is acknowledged that the process of land becoming salt affected is gradual. The actual statistics about hectares of salt affected land in the Murray Darling Basin is not available. The National Land and Water Resources Audit (NLWRA 2001) used a parameter 'salt affected land or land at risk of becoming salt affected that means a land that as a water table within 2 meters of the ground surface. As stated before, this model uses the parameter that is consistent with the one used by the National Land and Water Resources Audit (NLWRA 2001).

Fraction of land either salt affected or at risk of becoming salt affected is a user controlled parameter. The default value is 0.1 that means a land control treatment is applied at 10% of the salt affected or at risk of becoming salt affected land.

Effectiveness of a control treatment is a treatment specific parameter. It is also a user controlled parameter. The default value is 0.5 (50% effective). A 50 % effective control treatment means that if applied it can bring about the half of the impact of a hypothetical fully effective control.

Time delay in a piece of land going out of risk of becoming salt affected is also user controlled. The default value is kept at 30 years.

Rate of land reclamation=cleared land either salt affected or at the risk of becoming salt affected*friction of land at risk of becoming salt affected on which control treatment is applied*effectiveness of control treatments./time delay between land at risk of becoming salt affected and land not at risk of becoming salt affected under a certain control treatment.

### 5.2.7 Rate of salt affected land returning to natural vegetation cover.

The model accommodates another pathway for the salt affected land, i e., the land is left out of agricultural operations. No further land reclamation control treatment is applied. Overtime, the unattended land starts to return to the bush/natural vegetation cover. The formulation that provides this rate is graphically shown as in the Figure 9

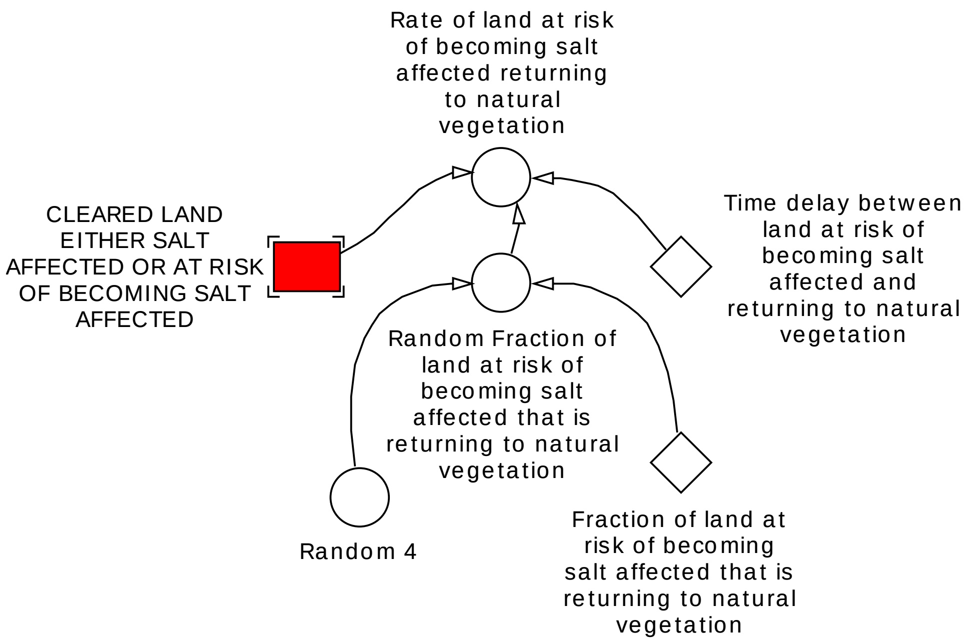


**Figure 9 Rate of land return to natural vegetation cover**

The rate of land returning to natural vegetation is defined as:

Rate of land returning to natural vegetation cover= Cleared land either salt affected or at the risk of becoming salt affected*Fraction of land at risk of becoming/time delay between land either salt affected or at the risk of becoming salt affected and returning to natural vegetation.

Both the fraction and the time delay are user controlled parameters. The default value is 0.5, i.e., 5%. The actual fraction may vary over the period of simulation. A random number generator (random(0, 1, 0.5)) fluctuates this fraction.

Time delay may vary based on a number of factors, e.g., location of a piece of land, type of vegetation and other geo-physical conditions. It is a user controlled parameter. The default value, i.e., the maximum time a piece of land takes in returning to its natural vegetation cover is kept at 50 years.

### 5.2.8 Delays

All time delays in the model are considered as material delays. Although the symptoms of land becoming salt affected, e.g., reduction in crop yields, salt crust, surface appearance and change in vegetation cover may appear after a certain time, the processes involved in a piece of land becoming salt affected start in an early phase. The simple formulation is shown below:

Time Delay = material/time taken

## 5.3 BUILDING CONFIDENCE IN MODEL: INTEGRATION, VERIFICATION AND VALIDATION (THE SECOND LEG OF VEE MODEL)

### 5.3.1 Integration

Forsberg, Mooz et al. (2005) defined integration as the successive combining and testing of system hardware assemblies, software components, and operator tasks to progressively pro eth performance and capability of all entities of the system. In terms of a System Dynamics model, it would mean the integration of modules to each other. Modules were incrementally integrated one by one with each other. A top down integration approach was adopted. Model behaviour was checked after each step in integration.

### 5.3.2 Verification and Validation

In Systems Engineering, confidence is progressively gained in a model or system through verification and validation. Verification ensures the model is built rightly, i.e, it does not has internal inconsistency or flaws in its equation formulations and is built conforming to the baseline/requirements ether identified at the start of modelling or evolved during the process. In development of a System Dynamics model, verification would mean that the governing business rules have been correctly identified and coded and the structure in which those rules operate results in correct replication of the reference modes of behaviour identified in earlier stages (McLucas 2005).

A mix of System Dynamics and Systems Engineering model verification and validation approaches were applied. Authors consider that a complete description of the verification and validation undertaken for this model is beyond the scope and available length of this paper. The issue of model verification and validation will be comprehensively addressed in the next paper in this series of research papers. A brief overview of the flow sequence, dimensional consistency and the mass balance test is below.

A flow sequence test was conducted to ensure the integrity of stocks and that the outflows do not precede inflows. Dimensional consistency was assured by:

a) using software that does not allow to simulate if there is dimensional inconsistency. Powersim Studio has been used to confirm dimensional consistency.
b) each equation was individually analysed to ensure dimensional consistency
c) a simple model was built without using complex technicalities including multi-dimensional arrays.

A mass balance test ensures that the functions performed by algebraic operators do not result in the inadvertent creation or destruction of flows (McLucas 2005). A mass balance test was performed to ensure that the algebraic operators do not result in inadvertent creation or destruction of flows. The method described by McLucas (2005) was used. A new variable called Delta was created for each module. Delta represented sum of all flows into a stock. The structure of the Delta check model is shown in the Figure 10. The delta check indicated zero mass balance error.

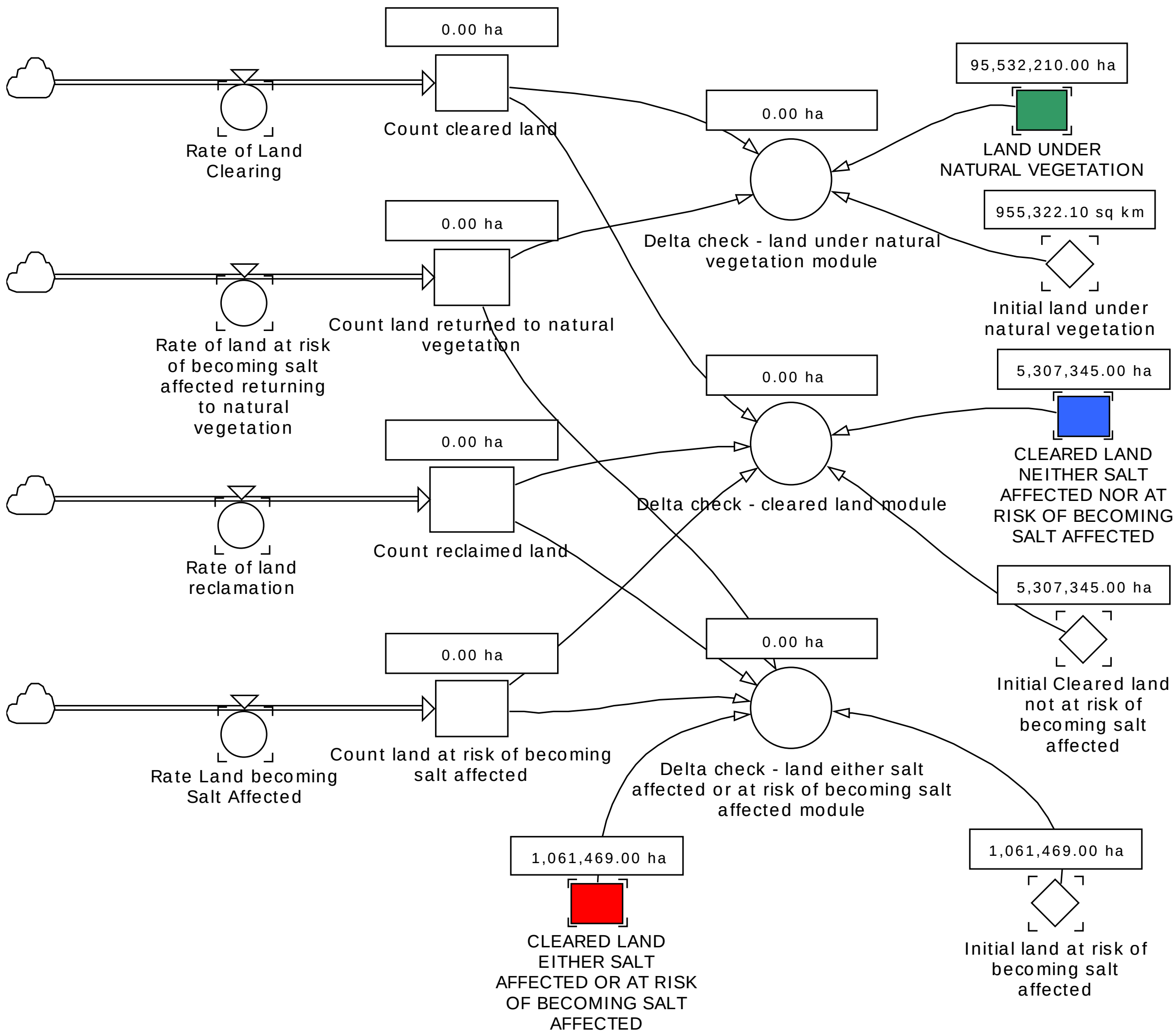


**Figure 10 Delta Check: Mass Balance Test of Model Structure and Behaviour**

# 6 SUMMARY AND CONCLUSION

This paper demonstrated the process in which Systems Engineering Vee Model was applied for developing a System Dynamics-based dryland salinity model. Basic requirements for the model were identified and listed at the start of the model building process. Each module was described with its stocks, flows and auxiliaries. Module verification tests like dimensional consistency, flow sequence and mass balance test were described.

System Dynamics model is a simpler system than the broad category of engineering systems for which Systems Engineering process is applied. However, there are certain model building aspects, like requirements identification, subsystem planning and model verification, in which the application of Vee Model can improve the quality of a System Dynamics model. It can reduce some of the inconsistencies in the model development process and can help in development of robust and 'responsive to purpose' models.

The use of the Vee Model can also provide a mechanism for model validation as it helps to emphasise the importance of planing and evaluation in almost all stages of model development. This application highlights the synergies between system engineering and System Dynamics and provides an avenue for further exploration of such synergies between the two methods to improve model quality.

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