CSIRO Land and Water

Indicator Frameworks for Assessing Irrigation Sustainability

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Executive Summary

This report summarises knowledge of sustainability, indicators, and particularly sustainability indicator frameworks. This knowledge delivers awareness of the tools available for the development of the Northern Australia Irrigation Futures (NAIF) Sustainability Framework.

A possible structure for the NAIF Sustainability Framework is proposed and outlined. It is based on three major parts:

1. Sustainability indicators;
2. Knowledge of function of irrigation systems; and
3. Management and planning guidelines.

Sustainability and sustainability indicators are introduced and discussed. To assess the sustainability of an irrigation system, sustainability indicators (SIs) must have the following desirable functions:

- Gauge sustainability of system elements (social, cultural, economic, environmental, institutional);
- Gauge sustainability of system attributes (e.g. groundwater, crops) and processes (e.g. deep drainage, cultivation) that make system elements; and
- Gauge sustainability at a range of spatial scales (field, farm, district, scheme, and catchment).

How sustainability indicators are structured and related in a framework determines the possible uses of a sustainability indicator framework. We propose criteria to analyse sustainability indicator frameworks:

- Identifies system attributes and distinguishes them from sustainability indicators;
- Identifies system processes and distinguishes them from sustainability indicators;
- Identifies sustainability indicators that gauge system processes and different aspects of each attribute;
- Structures sustainability indicators according to spatial scales;
- Identifies system capacity by proposing threshold values for system attribute and process sustainability indicators; and
- Illustrates balance between states of sustainability indicators.

Nine natural resource sustainability indicator frameworks are analysed. Each sustainability indicator framework is described, its use explained, and tested against the criteria listed above. Benefits and shortcomings of sustainability indicator frameworks are presented. Eight key criteria for assessing the usefulness of sustainability indicators frameworks are developed:

1. Incorporates or allows the incorporation of threshold values;
2. Illustrates balance between states of sustainability indicators;
3. Identifies specific relationships between sustainability indicators;
4. Uses hierarchy to promote systemic thinking and assist in sustainability indicator selection;
5. Can be used to review systems at a range of spatial scales;
6. Facilitates participatory research;
7. Integrates scientific and experiential knowledge; and
8. Simulates and tests planning and management scenarios.

Bayesian Belief Networks satisfy seven of the eight assessment criteria. A Bayesian Belief Network is a conceptual representation of a system that links indicators with arrows that represent the flow of cause and effect.

The AMOEBA satisfies six of the eight assessment criteria. The AMOEBA is a sustainability presentation tool that displays sustainability indicators around a sustainability zone ‘ring.’

We recommend adoption of the AMOEBA SI Framework and Bayesian Belief Networks to help progress development of the NAIF Sustainability Framework. The AMOEBA SI Framework to accomplish the following: facilitation of sustainability indicator development; facilitation of threshold setting; presentation of sustainability assessments; and facilitation of stakeholders’ understandings of sustainability. The Bayesian Belief Networks for simulating and testing planning and management scenarios.

Table of Contents

1. Introduction

The Northern Australia Irrigation Futures (NAIF) project was initiated in late 2003 to develop a sustainability framework. This sustainability framework is envisaged as a tool to facilitate more thorough debate and better decision making regarding irrigation in northern Australia.

Too often, irrigation developments have delivered short-term economic benefits without regard for long term costs associated with environmental degradation. There is a need for greater awareness of costs and benefits of irrigation developments. A better understanding of irrigation developments, and what makes them sustainable, ensures long-term costs and benefits are incorporated into decision making.

Today's irrigation developments in northern Australia are designed and managed in ways not suitable for the region; they are either copied from developments in other parts of the world or from developments of the past. Traditional problems are still occurring: rising water tables; soil salinisation; contamination of waterways; salt water intrusion etc. There is a need to improve the design and management of new and existing irrigation developments. There is a need to promote evolving knowledge to support the adoption of alternative designs and management practices.

The NAIF Sustainability Framework (Figure 1.1) will meet these needs by integrating and delivering the following information:

- Sustainability indicators (SIs) to guide monitoring and assessment of irrigation agroecosystem attributes and processes (see Glossary, p.45);
- Knowledge on the function of irrigation agroecosystems in northern Australia to support understanding, decision making, planning, and management; and
- Management and planning guidelines to guide the development of site specific plans and management strategies.

This information could form three parts in the NAIF Sustainability Framework (Figure 1.1). Arrows represent relationships between parts. These relationships, detailed on the next page, describe the operational functioning of this sustainability framework.

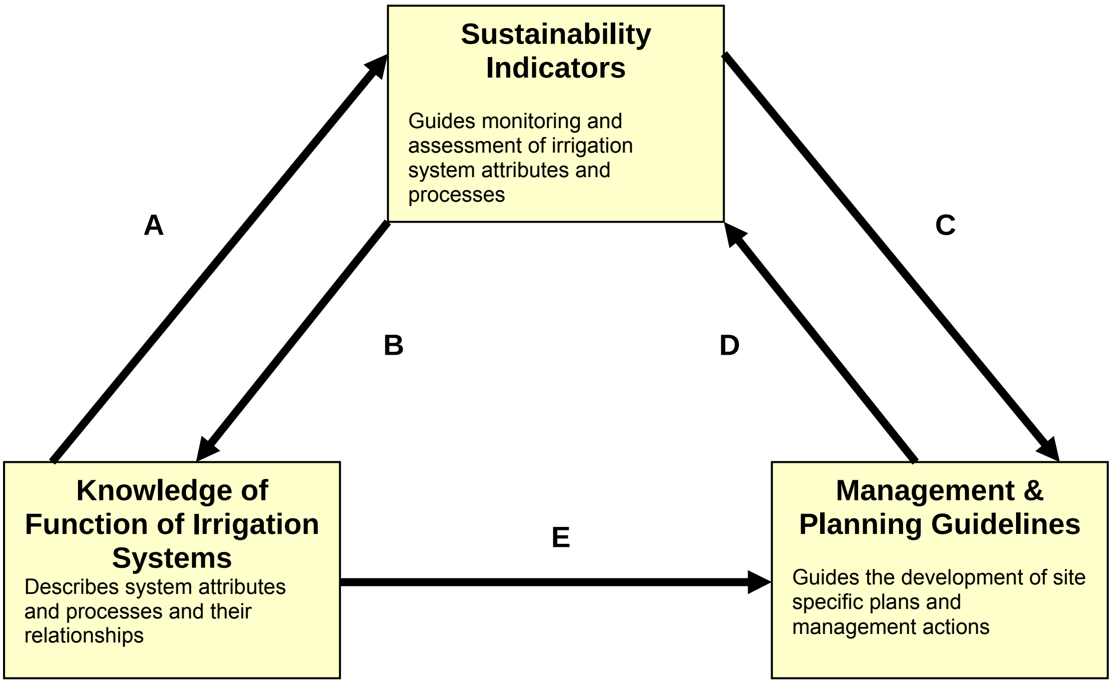


FIGURE 1.1
NORTHERN AUSTRALIA IRRIGATION FUTURES SUSTAINABILITY FRAMEWORK

Relationship A
Knowledge of how irrigation agroecosystems function suggests which SIs are appropriate for gauging sustainability. For example, knowledge of deep drainage suggests SIs to gauge effects on groundwater.

Relationship B
Applying SIs provides monitoring data, which improves our knowledge of irrigation agroecosystem function. For example, monitoring deep drainage with SIs improves knowledge of how deep drainage affects groundwater.

Relationship C
The application of SIs highlights problems for management to address. For example, data collected from groundwater monitoring suggests that deep drainage is excessive and needs to be managed.

Relationship D
Management and planning guidelines prescribe management actions for particular scenarios and propose SIs to measure the performance of those actions. For example, management and planning guidelines propose SIs to measure improvements in groundwater quality after re-scheduling irrigation to minimise deep drainage.

Relationship E
Management and planning guidelines are adapted to incorporate evolving knowledge of irrigation agroecosystem function. For example, it is discovered that a particular irrigation schedule minimises deep drainage: management and planning guidelines are adapted to include the improved irrigation schedule as a response to deep drainage problems.

Interaction between Framework Parts

An interaction between two parts will likely trigger further interactions, resulting in a sequence of interactions. For example, the application of SIs identifies that groundwater quality is unsustainable (relationship C); management and planning guidelines prescribe actions to remediate groundwater quality problems and suggest SIs for assessing performance of those actions (relationship D); and the application of SIs to assess performance of management actions provides data that improves knowledge of how deep drainage affects groundwater quality (relationship B).

Report Objective

The objective of this report is to identify one or more useful SI frameworks for assessing sustainability. Criteria are established and used in an attempt to make the identification process objective.

Existing Sustainability Indicator Frameworks

Nine natural resource sustainability indicator frameworks are reviewed. Searches of CSIRO's library catalogue, the internet, and journal databases were used to find these frameworks in books, journal articles, and the grey literature.

2. Methods

The methods used to select a sustainability indicator framework for the NAIF Sustainability Framework are given in Figure 2.1.

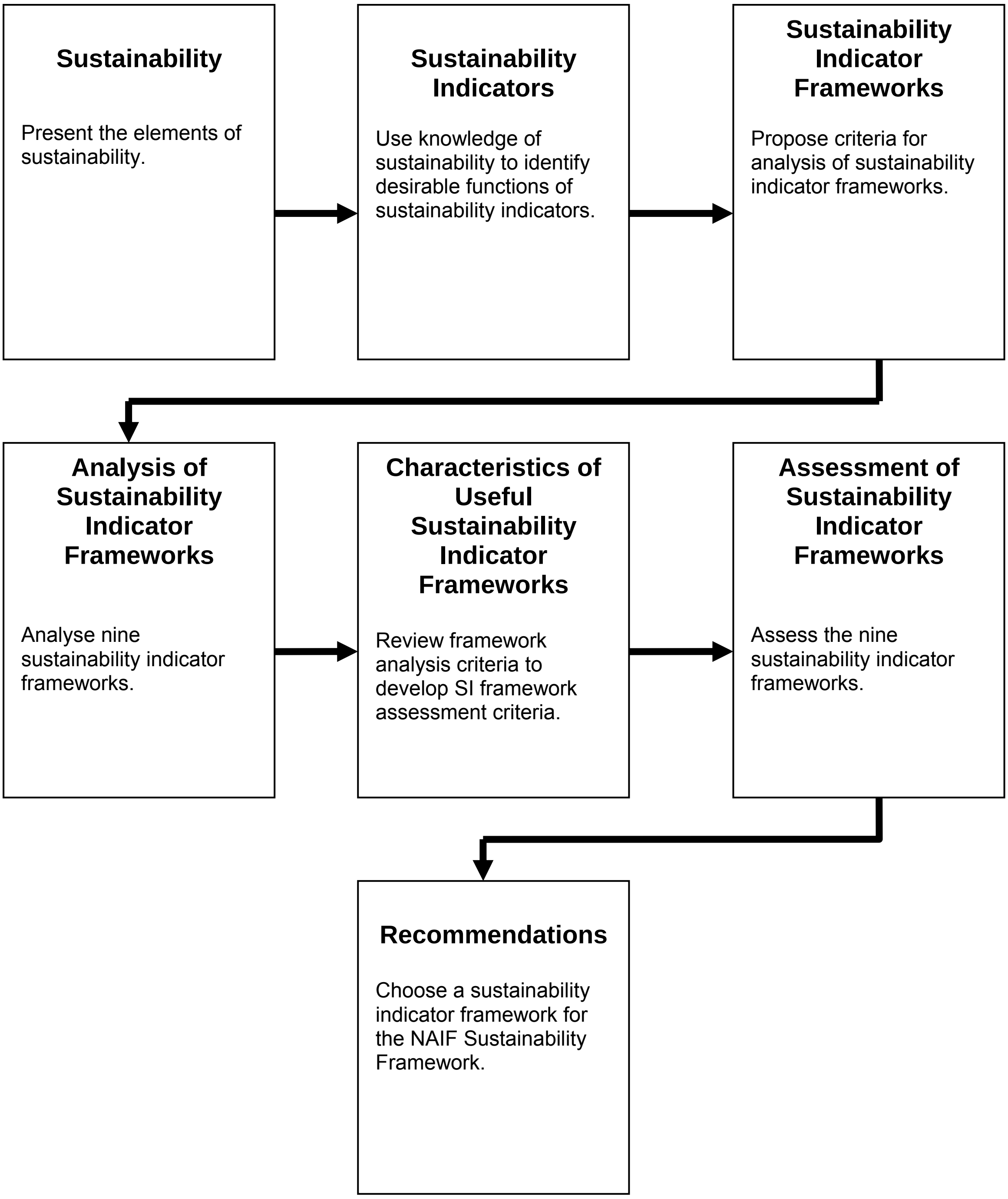


FIGURE 2.1
METHODS USED TO SELECT A SUSTAINABILITY INDICATOR FRAMEWORK FOR THE NAIF SUSTAINABILITY FRAMEWORK

3. Sustainability

Sustainability is an evolving concept, but the following points occur in definitions:

1. Equity between members of the present generation;
2. Equity between members of current and future generations;
3. Balance between system elements: social, economic; environmental; institutional; cultural; and
4. System capacity limits to support human populations.

The concept of sustainable development, presented internationally by the World Commission on Environment and Development in 1987 was defined as ‘meeting the needs of the present without compromising the ability of future generations to meet their own needs.’ David Schaller’s definition outlines three dimensions of sustainable development: ‘Achieving the *ecological balance* which allows *economic prosperity* and *social equity* to be achieved across generations’ (Sustainable Washington 2004).

These definitions introduce equity (see Glossary p. 46), not only between generations, but among people of the same generation. David Schaller’s definition also emphasises balancing economic, social, and ecological elements. In addition to these elements, some people include institutional and cultural elements (Bell & Morse 1999).

James Coomer defines ‘sustainable society’ rather than sustainable development: ‘A sustainable society is one that lives within the self-perpetuating limits of its environment. That society is not a ‘no growth’ society - it is, rather, a society that recognizes the limits of growth and looks for alternative ways of growing’ (Sustainable Washington 2004). This definition outlines the fourth element of sustainability: system limits to support human populations.

Izac & Swift 1994, propose initial and revised sustainability definitions for agriculture. They initially define a sustainable cropping system as one that achieves an acceptable level of production of harvestable yield, which shows a non-declining trend from cropping cycle to cropping cycle, over the long term. Izac & Swift 1994, acknowledge that this definition only addresses one element of sustainability: sustainability of farming system production. Their revised definition includes the following elements:

- Sustainability at a range of spatial scales (field, farm, and village) – equity between members of the current generation;
- Sustainability of all farming system outcomes (products, by-products, and ecological impacts) – balance between system elements;
- Capacities of ecosystems to respond to change – system limits; and
- Sustainability of a farming system in the context of change – change occurs through system processes.

Sustainability is now seen by some as a process rather than a state (Freebairn & King 2003; Bell & Morse 1999; Cox et al. 1997). The aim of the sustainability process is to move towards systems that we view as more desirable. In the context of natural resource management, communities and governments must continuously work through this process in a collaborative manner to ensure that the sustainability journey is shared. The next section is concerned with the use of sustainability indicator frameworks to monitor and guide the evolution of more desirable systems.

4. Sustainability Indicator Frameworks

Indicators have been used traditionally by biologists to assess ecosystem health (Bell & Morse 1999). More recently, indicators have been broadened to gauge aspects of societies, economies, institutions, cultures, and our living environment as a whole.

Sustainability indicators (SIs) describe aspects of the sustainability of systems. The sustainability of various attributes and processes of a system are gauged with different SIs. Further, different indicators gauge different systems. For example, a different set of SIs is used to assess the sustainability of an irrigation farm compared with an aquaculture farm. However, some SIs are the same for both of these systems, such as *net profit,* which gauges financial performance. Some biophysical SIs relevant to irrigation agroecosystems are presented in Appendix 1.

The definitions presented in the previous section elucidate that sustainability is multi-dimensional. SIs must measure the various dimensions of sustainability. To achieve this, SIs must gauge the following:

1. Sustainability of system elements;
2. Sustainability of system attributes and processes that make these elements; and
3. Sustainability at a range of spatial scales.

It is important to note that the temporal dimension of sustainability is inherently treated by collecting a time series of SI values to generate SI trends: SI trends illustrate temporal dimension.

SIs structured in a list, table, diagram, or model constitute a SI framework. How SIs are structured determines the functions of a SI framework. In consideration of the various dimensions of sustainability, we believe that a SI framework should have the following functions:

1. Identifies system attributes and distinguishes them from SIs;
2. Identifies system processes and distinguishes them from SIs;
3. Identifies SIs that gauge system processes and different aspects of each attribute;
4. Structures SIs according to spatial scales;
5. Identifies system capacity by proposing threshold values for system attribute and process SIs; and
6. Illustrates balance between states of SIs.

These points, evolved from sustainability definition elements, are used as criteria to analyse nine SI frameworks presented in this section. These criteria are discussed in more detail below.

Identifies system attributes and distinguishes them from SIs.
Attributes of a system must be clearly identified as components of a system. System attributes are separate from SIs; SIs gauge system attributes. For example, groundwater is an attribute of a biophysical system: to measure the sustainability of this attribute we use SIs such as groundwater level and salinity. Distinguishing system attributes from SIs ensures a clear understanding of what SIs gauge.

Identifies system processes.
The processes of a system must be clearly identified. System processes influence system attributes. For example, groundwater (attribute) is influenced by deep drainage and lateral flow (processes). Identifying and understanding processes improves our capacity to identify change in a system and provides understanding of how change occurs.

Identifies SIs that gauge system processes and different aspects of each attribute.
A SI framework must identify SIs that gauge system attributes and processes. A range of SIs is needed to gauge an attribute. For example, groundwater (attribute) is gauged with salinity, depth to groundwater, and pesticide concentration (SIs). Usually only one SI is needed to gauge a process. For example, rainfall (SI) gauges rainfall (process).

Structures SIs according to spatial scale.
A SI framework must structure SIs according to the spatial scales. For example, sediment load is listed in a SI framework as a catchment SI, for it is applicable to the catchment scale. This way of structuring improves the organisation of SIs and requires consideration of how different sets of SIs are needed to measure sustainability at different spatial scales.

Identifies system capacity by proposing threshold values for attribute and process SIs.
A SI framework must propose threshold values for all SIs. A threshold value indicates the sustainable condition (desired state) of an attribute or process. Threshold values allow comparison between existing and desired states to determine whether management action is required.

Illustrates balance between states of SIs.
The states of SIs must be presented to allow the visualisation of the balance between them.
This can be done using charts, diagrams, or tables. An example: Figure 4.1 presents the level of sustainability for the states of three water supply system SIs: supply reliability; distribution ratio; and discharge ratio. This figure shows that the SIs' states are not well balanced: states of distribution ratio and discharge ratio are much more sustainable than the state of supply reliability. By illustrating balance between SIs' states, it is easier to see which states need to be improved. Another advantage is that trends can be identified using a time series of illustrations. For example, a 10 year time series of the Bar Chart in Figure 4.1 may show that 'Supply Reliability' fluctuates.

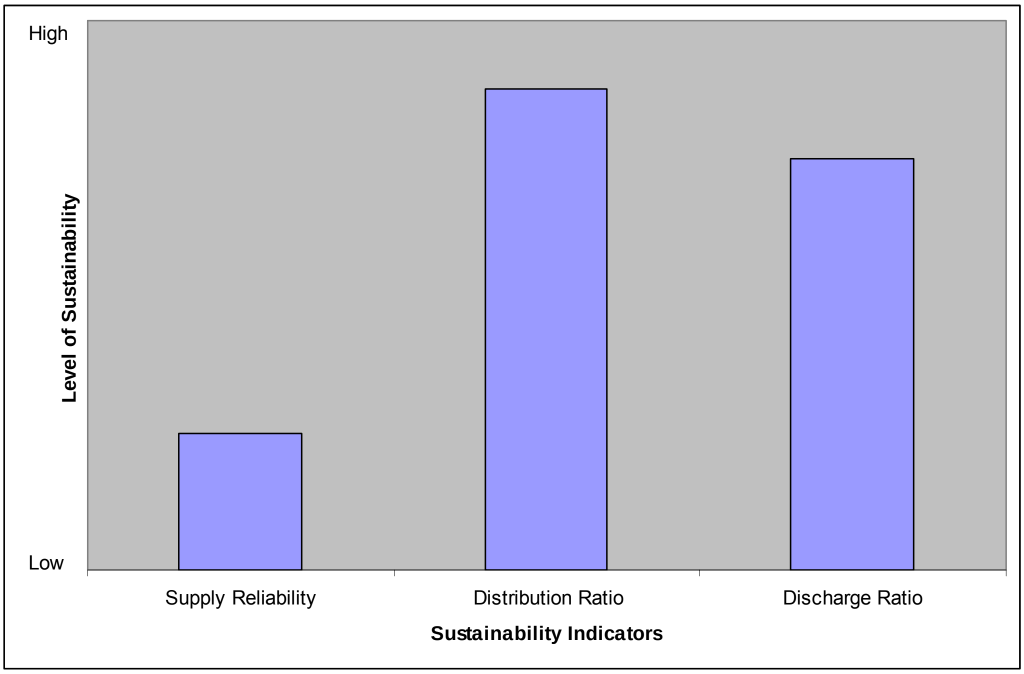


FIGURE 4.1
BAR CHART USED TO ILLUSTRATE BALANCE BETWEEN SIs' STATES FOR THE SYSTEM ATTRIBUTE: WATER SERVICE PROVISION

Analysis of Sustainability Indicator (SI) Frameworks

4.1 State and Control

Bell & Morse 1999 outline the State and Control SI framework and suggest that it is the simplest. This framework divides SIs into state and control groups. State SIs describe the state of a variable, e.g. pH of soil. Control SIs are also referred to as pressure SIs, process SIs, or driving force SIs. A control SI gauges a process that influences a state SI. An erosion SI and the rate at which pesticides enter rivers are two examples of control SIs.

This SI framework links a state SI with a control SI. An example: the rate of erosion (gauged by a control SI) influences the concentration of TDS in river water (state SI). As the rate of erosion increases, so too does the concentration of TDS (relationship). Table 4.1 lists some State and Control indicators that are linked. Links are explained in the 'Relationship' column.

TABLE 4.1
STATE AND CONTROL INDICATORS LINKED BY RELATIONSHIPS

State Indicator	Control Indicator	Relationship
Total suspended solids (mg/L)	Erosion (t/ha/yr)	Increased erosion leads to an increase in the quantity of soil transported to waterways. Soil in rivers and streams is indicated by total suspended solids.
Groundwater level (m)	Deep drainage (mm/day)	Water from rainfall and irrigation passes down below the root zone and contributes to rising groundwater.
Land value per household ($)	Global warming (°C/yr)	Global warming may cause desertification in some areas thereby decreasing the value of farming land.
Percent of native vegetation (%)	Land clearing (ha/yr)	Land clearing reduces the percentage of area with native vegetation.
Importance of a sacred Aboriginal site	Earthworks	Earthworks for development may destroy a sacred aboriginal site. The value of this site is then also destroyed.

Identifies system attributes and distinguishes them from SIs.
System attributes are not clearly identified or distinguished from SIs. For example, the SI framework infers that the SI 'groundwater level' gauges the attribute 'groundwater', but 'groundwater' is not explicitly identified as an attribute. In this example, it is obvious that 'groundwater level' refers to the attribute 'groundwater', however it is not always obvious which attribute an SI refers to: the SI 'lateral flow' also refers to the attribute 'groundwater.'

Identifies system processes and distinguishes them from SIs.
One process (e.g. erosion) is shown to influence the state of one attribute (e.g. turbidity of river water). In reality, more than one process influences an attribute. For example, turbulence also influences quality of river water.

System processes are not clearly distinguished from SIs. For example, 'Erosion' is itself a process, but this is not explicitly stated.

Identifies SIs that gauge system processes and different aspects of each attribute.
Only one aspect of each attribute is gauged with a SI. For example, only the percentage of native vegetation is gauged: other aspects such as disease outbreak frequency and woody weed abundance are not gauged. SIs that gauge processes are proposed (e.g. land

clearing). Each process SI is linked with an attribute SI and the linking relationships are explained.

Structures SIs according to spatial scale.
It is not clear at which scales the proposed SIs are applicable, as the SIs are not structured according to spatial scale.

Identifies system capacity by proposing threshold values for system attribute and process SIs.
Threshold values are not proposed.

Illustrates balance between states of SIs.
States of SIs (e.g. sustainable / unsustainable) are not presented in this SI framework. The structure of the SI framework does not allow an illustration of balance between states of SI's: a table, chart, or diagram is not proposed to present SIs' states.

Other Comments
Relationships between system attribute SIs and process SIs are effectively shown. However, by linking each attribute SI with only one process SI, system complexity is not adequately addressed. This is a simple framework that clearly presents relationships between SIs.

4.2 Driving Force, State and Response

4.2.1 United Nations' Working List of Indicators of Sustainable Development

The United Nations developed a Driving Force, State, and Response SI framework. This framework is presented in the Agenda 21 document, which flowed on from the Rio de Janeiro Conference on Sustainable Development in 1992 (Bell & Morse 1999). UN 1996, suggests that this SI framework is flexible and allows countries to choose SIs according to national priorities, problems, and targets. A sample of this framework is shown in Table 4.2.

TABLE 4.2
THE UNITED NATIONS' DRIVING FORCE, STATE, AND RESPONSE SI FRAMEWORK

	Driving Force	State	Response
SOCIAL Promoting education, public awareness and training	• Rate of change of school-age population • Primary school enrolment ratio (gross and net) • Secondary school enrolment ratio (gross & net) • Adult literacy rate	• Children reaching grade 5 of primary education • School life expectancy • Difference between male and female school enrolment ratios • Women per hundred men in the labour force	• Gross Domestic Product spent on education
ECONOMIC Financial resources and mechanisms	• Net resources transfer / Gross National Product • Total Official Development Assistance given or received as a percentage of Gross National Product	• Debt / Gross National Product • Debt service / export	• Environmental protection expenditures as a percent of Gross Domestic Product • Amount of funding for sustainable development
ENVIRONMENTAL Promoting sustainable agriculture and rural development	• Use of agricultural pesticides • Use of fertilizers • Irrigation percent of arable land • Energy use in agriculture	• Arable land per capita • Area affected by salinisation and waterlogging	• Agricultural education
INSTITUTIONAL Integrating environment and development in decision-making	None.	None.	• Sustainable development strategies • Programme of integrated environmental and economic accounting • Mandated Environmental Impact Assessment • National councils for sustainable development

Source: UN 1996

4.2.2 OECD's Core Set of Environmental Indicators

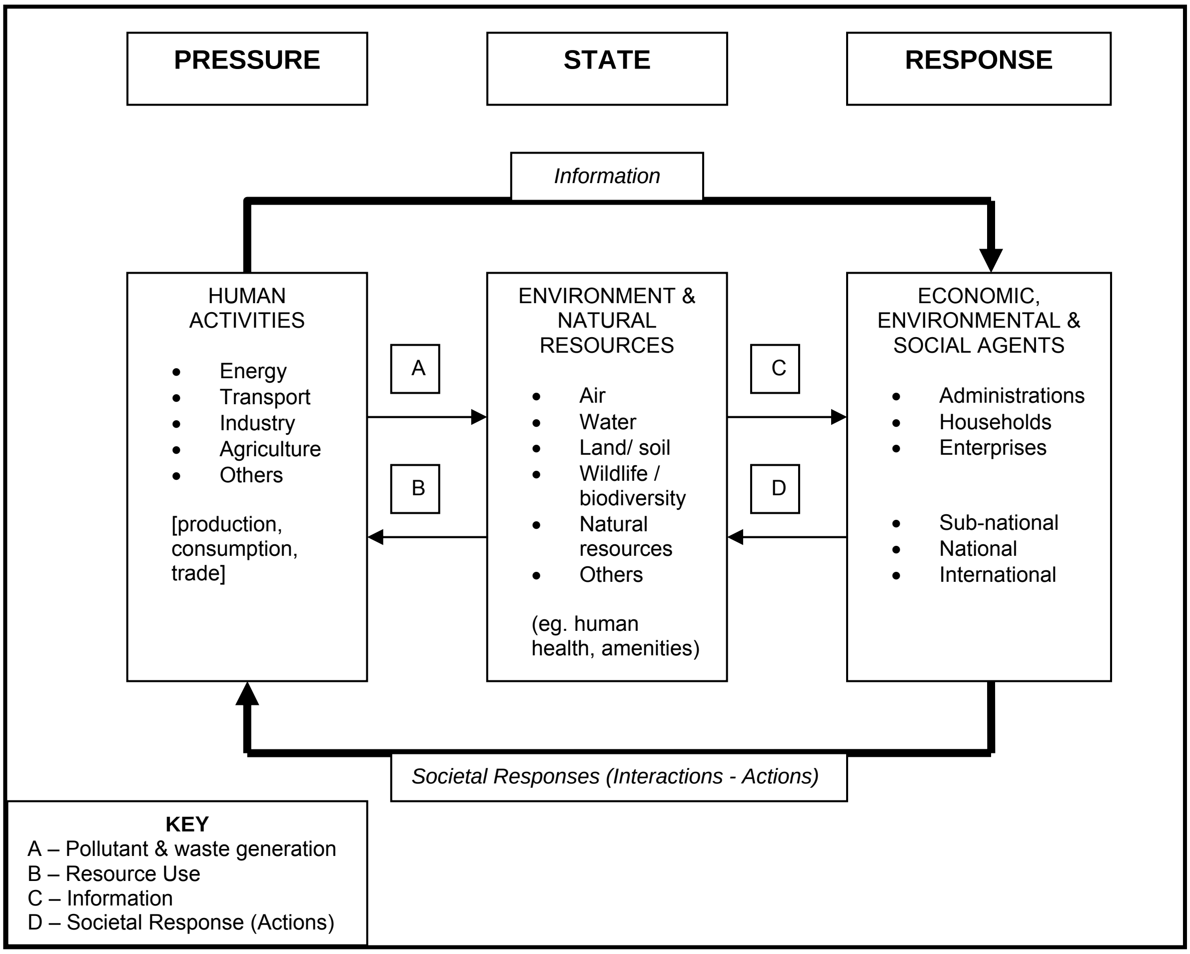
The Organisation for Economic Co-operation and Development (OECD) 2003, proposes that environmental SIs are cost effective and valuable tools. By providing a framework of environmental SIs, OECD can assist countries to 'build a capacity to monitor and assess environmental conditions and trends so as to increase their accountability and to evaluate how well they are satisfying their domestic objectives and international commitments.'

In 1994, OECD developed a core set of environmental SIs in a Pressure, State, and Response SI framework. This SI framework is used by all OECD member countries, including Australia, for State of the Environment Reporting. This SI framework is a modification of UN's SI framework; the SI title 'Driving Force' is replaced with 'Pressure'.

The philosophy behind the design of this framework is outlined by OECD 2003:

"Human activities exert pressures on the environment and affect its quality and the quantity of natural resources (state); society responds to these changes through environmental, general economic and sectoral policies and through changes in awareness and behaviour (societal response)."

The Pressure-State-Response model used by OECD to classify environmental SIs is given in Figure 4.2.



Source: OECD 2003

FIGURE 4.2
OECD'S PRESSURE-STATE-RESPONSE MODEL OF CLASSIFYING ENVIRONMENTAL INDICATORS

The OECD further classifies environmental SIs into issues as outlined in Table 4.3.

TABLE 4.3
OECD FRAMEWORK CONTAINING TWO ISSUES AND RELATED SUSTAINABILITY INDICATORS

Issue	Pressures	States	Responses
Eutrophication	Nutrient balance – emissions of nitrogen and phosphorus in water and soil	Biological oxygen demand, dissolved oxygen and concentrations of phosphorus and nitrogen in inland and marine waters	Population connected to biological and/or chemical sewerage treatment plants
Soil Degradation	Erosion risks: potential and actual use of land for agriculture	Degree of top soil loss	Rehabilitation

Source: OECD 2003

Identifies system attributes and distinguishes them from SIs.
System attributes are not clearly identified or distinguished from SIs. For example, the SI 'degree of top soil loss' refers to soil, but 'soil' is not explicitly identified as an attribute.

Identifies system processes and distinguishes them from SIs.
This structure divides processes into two kinds: pressure processes and response processes. System processes are not clearly distinguished from SIs. For example, 'Rehabilitation' is itself a process, but this is not explicitly stated.

Identifies SIs that gauge system processes and different aspects of each attribute.
The SI frameworks proposed by the UN and OECD identify SIs that gauge different aspects of each attribute. These SIs are identified in the 'State' column. For example, in Table 4.3 'number of children reaching grade 5' and 'school life expectancy' are two SIs that measure aspects of the attribute 'children.'

Process SIs are identified in the 'Pressure' and 'Response' columns. In UN's SI framework, groups of Driving Force SIs and groups of Response SIs are linked with groups of 'State' SIs: there are no direct linkages between particular SIs of the three categories. OECD's SI framework directly links a particular Pressure SI (e.g. erosion risk) and Response SI (e.g. rehabilitation) with a particular State SI (e.g. degree of top soil loss).

Structures SIs according to spatial scale.
The UN's SI framework is designed for national sustainability assessment: SIs are proposed for only the national scale. There is no spatial scale specified for OECD's SIs.

Identifies system capacity by proposing threshold values for system attribute and process SIs.
Threshold values are not proposed. The UN suggests that a SI framework without threshold values allows a nation to compare its conditions (indicated by SI values) with the conditions experienced by other nations. This circumvents the need for identifying ideal SI states. Desired SI states can be determined by looking at SI states for nations with admirable conditions.

Illustrates balance between states of SIs.
States of SIs (e.g. sustainable / unsustainable) are not presented in this SI framework. The structure of the SI framework does not allow an illustration of balance between states of SI's: a table, chart, or diagram is not proposed to present SIs' states.

Other Comments
Disregarding OECD’s Pressure-State-Response model and viewing only the SI frameworks presented in Tables 4.2 and 4.3, one assumes that cause and effect flows in only one direction: Driving Force processes affect attributes’ States, which affect society’s Responses. OECD’s model dispels this assumption and clearly illustrates other interactions between Driving Forces, States, and Responses. This model gives SIs context by identifying system elements that are measured.

Response SIs directly gauge the efforts of community to progress sustainability. This inclusion is useful because such SIs identify how adequate our effort and actions are.

OECD’s version of this framework uses issues (e.g. eutrophication) to categorise system attributes, processes, and their SIs. This ensures that SIs are selected for a particular purpose and avoids unnecessary inclusion of SIs.

4.3 Condition and Trend

Walker & Reuter 1999, propose a Condition and Trend SI framework for catchment health assessment. The purpose of this SI framework is to provide landholders, catchment groups, catchment and land protection boards, and rural communities with a tool to benchmark and monitor the condition of land and water resources in catchments (Walker & Reuter 1996). SIs are targeted at the field, farm, and catchment scales and cover farm productivity, financial performance, product quality, soil health, water quality, and landscape integrity (Walker & Reuter 1996).

TABLE 4.4
A SAMPLE OF WALKER & REUTER’S INDICATOR FRAMEWORK FOR CATCHMENT HEALTH ASSESSMENT

Condition / Trend	Scale	Indicator	Description of How to Measure	Meaning of Measurement	Thresholds / Comments		
					Good	***Fair***	***Poor***
Condition	Paddock	Water Intake Rate	Time the rate of entry of water into the soil	Infiltration	>70 mm/hr	10-30 mm/hr	0-10 mm/hr
Condition	Catchment	Tree cover	Visual estimate of % tree cover	Loss of ecological function, landscape dysfunction	>30%	5-30%	<5%
Trend	Paddock	Bare Soil	Visual estimate of % bare soil	Erosion risk, sediment movement to streams	0-10%	10-30%	>30%
Trend	Catchment	Depth to Water Table	Depth from surface or from surveyed datum to top of water table	Changes in local or regional recharge, likelihood of waterlogging, salinisation etc.	>3m	2-3m	<2m

Source: Walker & Reuter 1996

Identifies system attributes and distinguishes them from SIs.
System attributes are not clearly identified. Attributes are referred to in the ‘Description of How to Measure’ column, but are not set out separately. For example, in the second row of

Table 4.4, the system attribute ‘soil’ is referred to in the fourth column: ‘time the rate of entry of water into the **soil**.’

Identifies system processes and distinguishes them from SIs.
Processes are identified in the ‘Meaning of Measurement’ column. Processes are not explicitly linked with attributes: relationships between an attribute and processes in the same row are implied, not described.

In some rows, a SI corresponds with, and indicates the occurrence of, processes and changes in attributes in the ‘Meaning of Measurement’ column. For example, the SI ‘depth to water table’ indicates the following: processes of waterlogging and salinisation; change in local or regional recharge. This information provides useful context for SIs, however, because there are no explanations of the SI-process links (e.g. depth to water table and regional recharge), understanding of how SIs indicate these processes and changes in attributes is not promoted.

Identifies SIs that gauge system processes and different aspects of each attribute.
Although not evident in the Condition and Trend SI Framework sample, SIs gauge different aspects of each attribute. For example, the attribute ‘soil’ is gauged with the following SIs: bare area; pH; soil consistence; soil strength; water intake rate etc. SIs that gauge processes are proposed. For example, the process ‘infiltration’ is gauged by the SI ‘water intake rate.’

Structures SIs according to spatial scales.
SIs are divided into two spatial scales: paddock and catchment. SIs presented are applicable to scales other than those suggested. For example, the SI ‘tree cover’, proposed for the catchment scale, can be applied to the farm scale.

Identifies system capacity by proposing threshold values for system attribute and process SIs.
Threshold values are proposed for all SIs. These values do not identify system capacity; they classify states: good; fair; and poor. This categorisation reflects assessment of catchment health rather than sustainability.

Illustrates balance between states of SIs.
States of SIs (good, fair, and poor) are outlined but cannot be illustrated with this SI framework. A table, chart, or diagram is not proposed to present SIs’ states.

Other Comments
SIs are categorised into condition and trend groups. Condition SIs ‘define the state of the system relative to a desired state.’ Trend SIs ‘measure how the system has changed.’ The use of this distinction is questionable because of the following:

- A time series of condition SI values form a trend; and
- Trend SI values can be compared with desired (threshold) values to assess condition.

The detail provided in this SI framework makes it a useful information source. Also, by providing ranges for thresholds, this framework supports the inexact nature of sustainability.

With some modification to this SI framework, states of SIs can be illustrated. Table columns are used to separate these states. Once a state is selected for each SI, appropriate table cells are marked. Table 4.5 is the modified version of the Condition and Trend SI Framework illustrating balance between SIs’ states.

TABLE 4.5
MODIFIED VERSION OF THE CONDITION AND TREND SI FRAMEWORK ILLUSTRATING STATES FOR EACH SI

Indicator	Good	Fair	Poor
Water Intake Rate			
Tree Cover			
Bare Soil			
Depth to Water Table			

4.4 System Division

There are a number of SI frameworks that divide SIs into broad categories. These SI frameworks are presented in policy style documents and do not incorporate methods for focusing on particular applications. Four examples are briefly introduced and a fifth is discussed in more detail. These SI frameworks are collectively assessed.

RIRDC 1997, proposes a SI framework to assess sustainable agriculture at farm, regional, and national scales. SIs are divided into the following categories:
1. Profitability;
2. Land and water quality to sustain production;
3. Managerial skills; and
4. Off-site environmental impacts.

SCARM 1998, proposes a SI framework to 'Assess Australia's Recent Performance' with regard to agricultural sustainability. SIs are divided into the following categories:
1. Long-term real net farm income;
2. Natural resource condition;
3. Off-site environmental impacts;
4. On-site Managerial skills; and
5. Socio-economic impacts.

MAF 1997, proposes a SI framework to assess the sustainability of farms with irrigated agriculture in New Zealand. SIs are divided into the following categories:
1. Economic;
2. Environmental; and
3. Social.

Cai et al 2001, propose a SI framework to analyse irrigation water management in the Aral Sea Region, Central Asia. SIs are divided into the following categories:
1. Water supply system reliability, reversibility, and vulnerability;
2. Environmental system integrity;
3. Equity in water sharing; and
4. Economic acceptability.

The Douglas Shire Sustainability Information System was developed by CSIRO Resource Futures for the Douglas Shire Council. It is based on a SI framework which divides SIs into the following categories: social; economic; and environmental (Figure 4.3). This information system can be accessed via a web-page and allows anyone with internet access to retrieve information on SIs and SI values.

It is suggested that this information system performs three functions:
- Enables the evaluation of the Shire's progress towards sustainability;

- Facilitates informed decision-making on resource use to achieve sustainability; and
- Ensures that business of the Shire Council is relevant to the realities experienced by the Shire.

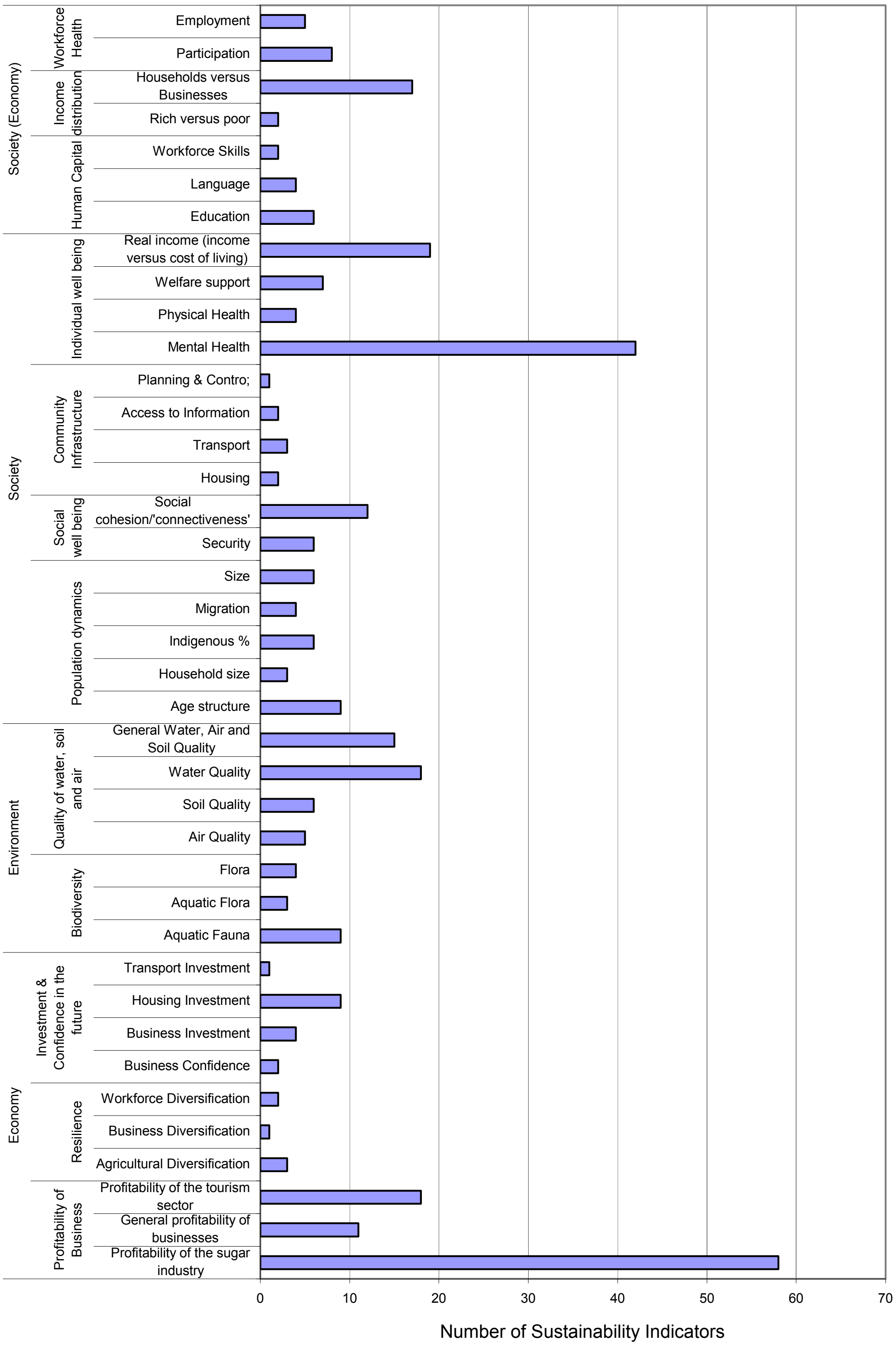


FIGURE 4.3

NUMBERS OF INDICATORS FOR EACH SYSTEM ATTRIBUTE USED BY THE DOUGLAS SHIRE SUSTAINABILITY INFORMATION SYSTEM

Identifies system attributes and distinguishes them from SIs.
System attributes are not clearly identified or distinguished from SIs. For example, in the framework proposed by RIRDC 1997, the SI 'salinity in streams' refers to streams, but 'streams' is not explicitly identified as an attribute.

Identifies system processes and distinguishes them from SIs.
System processes are not clearly identified or distinguished from SIs. For example, in the System Division SI Framework proposed by Muller 1998, the SI 'residue treatment' is itself a process, but this is not clearly stated.

Identifies SIs that gauge system processes and different aspects of each attribute.
SIs gauge different aspects of most attributes. For example, in the System Division SI Framework proposed by SCARM 1998, the attribute 'soil' is gauged with the following SIs: acidity; sodicity; and nutrient balance. SIs that gauge processes are proposed. For example, SCARM 1998 proposes the SI 'water utilisation by vegetation', which is also a process.

Structures SIs according to spatial scales.
For all System Division SI Frameworks, except the one proposed by RIRDC 1997, SIs are proposed for only one spatial scale: SCARM's framework is for the national scale; MAF's framework is for the farm scale; Cai et al's framework is for the basin scale; and CSIRO Resource Futures' framework is for the shire scale. RIRDC 1997 divides SIs into two spatial scale categories: regional/national; and farm.

All System Division SI Frameworks have some SIs that are applicable to spatial scales other than those suggested. For example, in Cai et al's framework, the SI 'equity in water sharing', proposed for the basin scale, can be applied to the district scale.

Identifies system capacity by proposing threshold values for system attribute and process SIs.
Threshold values are not proposed for SIs.

Illustrates balance between states of SIs.
States of SIs (e.g. sustainable / unsustainable) are not presented in this SI framework. The structure of the SI framework does not allow an illustration of balance between states of SI's: a table, chart, or diagram is not proposed to illustrate SIs' states.

Other Comments
System Division SI Frameworks simply divide SIs into broad categories. Categorisation is useful for organising information, but it can limit thinking: listing indicators under categories prompts considering each SI in the context of its heading only. In this way, SIs in different categories are seen to be separate, not related. For example, in the System Division SI Framework proposed by MAF 1997, the SI 'quantity produced' is considered in context of its heading 'Economic'; the relationship between 'quantity produced' and 'daily volumes of irrigation' is not apparent because 'daily volumes of irrigation' falls under a different heading: 'Environment.'

4.5 Sustainability Criteria

Some people have proposed sustainability criteria to guide the categorisation of SIs. Two Sustainability Criteria SI frameworks are presented: *System Products*; and *Productivity, Efficiency, Resilience, Biodiversity, Rules for Resource Management, and Satisfaction of Basic Needs.*

4.5.1 System Products

Izac and Swift 1994, propose a SI framework based on scales (cropping system, farm and village) and products (main products, by-products, and amenities). This SI framework was developed to provide a pragmatic and measurable definition of sustainability relevant to small-scale farming in sub-Saharan Africa. The philosophy behind the products/by-products/amenities classification is explained:

'Agricultural systems are established to deliver **products**. The production process causes change to the landscape harbouring the agricultural production system, generating benefits (**amenities**) and causing impacts (**by-products**).'

A sample of this framework is presented in Table 4.6.

TABLE 4.6
A SAMPLE OF A SUSTAINABILITY FRAMEWORK FOR A SUB-SAHARAN AGROECOSYSTEM

	Cropping system	Farm	Village
Products	• ratio of annual yield for all products to potential and/or farmer's target yield	• profit of farm production • ratio of profit to farmers' target income	• economic efficiency • social welfare
By-products	• soil pH • soil acidity • exchangeable aluminium content • soil loss • soil compaction • organic matter • abundance of key pest and weed species	• ratio of aggrading to degrading land area • nutritional status of household	• nutritional status of community • stream turbidity • nutrient concentration • acidity • human disease vectors • biodiversity and complexity
Amenities	None	• drinking water quality • source and availability of fuel	• drinking water availability

Source: Izac and Swift 1994

4.5.2 Productivity, Efficiency, Resilience, Biodiversity, Rules for Resource Management, and Satisfaction of Basic Needs

Muller 1998, proposes a sustainability assessment framework based on a number of sustainability criteria: productivity; efficiency; resilience; biodiversity; rules for resource management; and satisfaction of basic needs. This SI framework was developed to assess the sustainability of agriculture in the Reventado River Watershed, Costa Rica. A sample of this SI framework for the farm scale is shown in Table 4.7. Household scale and watershed scale sections of the framework are not shown. Also, the "Rules for Resource Management" criteria is omitted because there are no SIs proposed for this criteria at the farm scale.

TABLE 4.7
A SAMPLE OF A SI FRAMEWORK FOR AGRICULTURAL SUSTAINABILITY ASSESSMENT AT THE FARM SCALE

Sustainability criteria	Environmental / biophysical indicators	Economic indicators	Social indicators
Productivity	• Average soil quality per farm	• Farm income per man-day total labor input • Income per day of family labour	• Farm income per capita
Efficiency	None	• Production costs per unit	• Farm household income
Resilience	• Area with potatoes and onions as % of total area planted • Area with legumes as % of total area cultivated • Percentage of fallow	• Income of onion and potato production as % of total farm income	• Education level of farmer. • Farmers provisions for health and old age
Biodiversity	• Area with low input crops as % of total area planted • Bushes, hedges and fallow as % of farm area	None	None
Satisfaction of basic needs	None	None	• Health impairment due to pesticide application • Ratio of farm household income to minimum income

Source: Muller 1998

Identifies system attributes and distinguishes them from SIs.
System attributes are not clearly identified or distinguished from SIs. For example, in the Sustainability Criteria SI Framework proposed by Izac and Swift 1994, the SI 'drinking water quality' refers to drinking water, but 'drinking water' is not explicitly identified as an attribute.

Identifies system processes and distinguishes them from SIs.
System processes are not clearly identified or distinguished from SIs. For example, in the Sustainability Criteria SI Framework proposed by Izac and Swift 1994, the SI 'soil compaction' is itself a process, but this is not clearly stated.

Identifies SIs that gauge system processes and different aspects of each attributes.
SIs gauge different aspects of each system attribute. For example, in the Sustainability Criteria SI Framework proposed by Izac and Swift 1994, the attribute 'drinking water' is gauged with two SIs: quality; and availability.

Very few SIs are used to gauge processes. For example, in the Sustainability Criteria SI Framework proposed by Muller 1998, none of the farm scale social SIs gauge processes. Another example: In Izac and Swift's Sustainability Criteria SI Framework, only two of seven cropping system SIs gauge processes: soil compaction; and exchangeable aluminium content.

Structures SIs according to spatial scales.
In Izac and Swift's Sustainability Criteria SI Framework, SIs are divided into three spatial scales: cropping system; farm; and village. Muller's SI Framework also divides SIs into three spatial scales: farm; household; and watershed. Some SIs in these frameworks are applicable to spatial scales other than those suggested. For example, in Izac and Swift's framework, the SI 'source and availability of fuel', proposed for the farm scale, can be applied to the village scale. However, overall these frameworks appear to match SIs and spatial scales very well.

Identifies system capacity by proposing threshold values for system attribute and process SIs.
Threshold values are not proposed for SIs.

Illustrates balance between states of SIs.
States of SIs (e.g. sustainable / unsustainable) are not presented in the Sustainability Criteria SI Frameworks. The structure of these frameworks does not allow an illustration of balance between states of SI's: a table, chart, or diagram is not proposed to illustrate SIs' states.

Other Comments
Sustainability criteria provide contexts for SIs. As for System Division SI Frameworks, these contexts make difficult the consideration of relationships between SIs that fall under different categories.

4.6 Risk Assessment Triggers

Sinclair Knight Mertz 2004, developed irrigation development guidelines for the Murray-Darling Basin Commission. These guidelines are designed to make proponents and authorities aware of the information to be provided in a development proposal and help them to understand the evaluation process (SKM 2004). These guidelines are grouped by issues and/or biophysical attributes and constitute a risk assessment framework (Table 4.8). This SI framework uses SIs and threshold values to assess the suitability of potential irrigation development sites. If the assessment deems the site "suitable", a site management plan and a site use license are drawn up.

TABLE 4.8
SOME IRRIDATION DEVELOPMENT RISK ASSESSMENT TRIGGERS FOR SALINITY/SODICITY, SURFACE WATER, AND GROUNDWATER

System Attributes / Issues	Minor Risk	Major Risk	Not Permissible
Salinity / Sodicity	• Low existing water table >4m • Deep root zone >80cm • Low salinity groundwater <300mg/l TDS • Low salinity irrigation groundwater <300mg/l TDS • Low natural salt in soil <0.5dS/m ECe	• High watertable >2m • Shallow root zone <50cm • High salinity groundwater >5000mg/l TDS • High salinity irrigation water >1500mg/l TDS • High natural salt in soil >2dS/m ECe	• >4.5dS/m ECe
Surface water	• Low levels of salinity, nutrients or other toxicants in water • Irrigation by low level sprinkler, micro irrigation, drip or subsoil irrigation • No receiving waters or drainage lines are within close proximity	• High levels of salinity, nutrients or other toxicants in water • High rate sprays/ guns, flood irrigation or long laterals • A major sensitive river, stream, lake or wetland is adjacent	
Groundwater	• Low existing watertable (>4m) • Low annual irrigation rate (<3ML/ha) • Low depth of applied water (<30mm/ application) • Sprinkler or micro irrigation • Heavy impervious soils (e.g. clay)	• High existing watertable (<2m) • High annual irrigation rate (>6ML/ha) • High depth of applied water (>50mm/ application) • High rate sprays or flood irrigation • Permeable porous soils (e.g. sands, gravels) or fractured rocky soils (e.g. granite)	• Rapidly rising watertable (<2m)

Source: EPA 2002 cited in SKM 2004

Identifies system attributes and distinguishes them from SIs.
Although not clear in the sample of SI framework provided, system attributes are identified: soil; groundwater; surface water; nutrients; vegetation; fauna; and cultural heritage. These attributes, together with two issues (salinity/sodicity and biodiversity), are used to categorise SIs.

Identifies system processes and distinguishes them from SIs.
System processes are not clearly identified or distinguished from SIs. For example, the groundwater SI 'low depth of applied water' refers to irrigation, but 'irrigation' is not explicitly identified as a process.

Identifies SIs that gauge system processes and different aspects of each attributes.
SIs gauge different aspects of each system attribute. For example, the attribute 'surface water' is gauged with seven SIs; only three are shown in the sample provided. Some SIs are used to gauge system processes that influence attributes. For example, the SI 'low annual irrigation rate' gauges the process 'irrigation', which influences the attribute 'groundwater.' In effect, such SIs indirectly measure system attributes.

Structures SIs according to spatial scales.
SIs are not structured according to spatial scale.

Identifies system capacity by proposing threshold values for system attribute and process SIs.
Rather than identifying system capacity, threshold values are used to classify risk to human health, environmental impact, and financial loss.

Illustrates balance between states of SIs.
States of SIs are divided into the following categories: minor risk; major risk; and non-permissible risk. A table, chart, or diagram is not proposed to present SIs' states.

Other Benefits / Drawbacks
This framework identifies risks to human health, environmental impact, and financial loss if irrigation was developed at a particular site. These guidelines approximate risk for each SI. A more accurate risk assessment process is outlined in the supporting document.

With some modification to SKM's Risk Assessment Triggers SI Framework, states of SIs can be illustrated. Table columns separate states and rows separate SIs. Once a state is selected for each SI, appropriate table cells are marked. Table 4.9 is the modified framework illustrating balance between SIs' states.

TABLE 4.9
MODIFIED VERSION OF SKM'S RISK ASSESSMENT TRIGGERS FRAMEWORK ILLUSTRATING STATES FOR EACH SI

Attribute	Indicator	Minor Risk	Major Risk	Non-Permissible Risk
Groundwater	Depth of existing water table			■
	Annual irrigation rate	■		
	Depth of applied water	■		
	Irrigation Method	■		

4.7 Threat Identification Model (TIM)

TIM (Threat Identification Model) is a framework that identifies sources of unsustainability with agricultural land management systems at the land unit scale (Smith et al 2000). It explicitly links defined hazards of land management practice options to land productivity and environmental integrity (Smith et al 2000). A decision support system linking TIM and a Geographical Information System (GIS) allows outputs, such as constraints to agriculture and site-specific best management practices, to be identified in a spatially explicit manner (Smith et al 2000). Rather than presenting a series of indicators to gauge sustainability, this framework identifies causes and effects of land degradation and assigns land management options to limit it.

Table 4.10 presents hazards and management guidelines for a particular land unit (field) of a farm located in the Crystal Creek Catchment, between Ingham and Townsville in north Queensland.

TABLE 4.10
THREAT IDENTIFICATION MODEL OUTPUT WHICH IDENTIFIES HAZARDS AND BEST MANAGEMENT GUIDELINES FOR A PARTICULAR LAND UNIT OF A SUGAR CANE FARM

Land Unit	Primary Hazards	Secondary Hazards	Best Management Guidelines
1127	• Soil acidification • Soil dispersion or surface crusting • Soil structural decline or compaction • Soil nutrient decline • Shallow topsoil or subsoil exposure • Waterlogging • Poor soil water retention • Acid sulphate soil disturbance • Groundwater fluctuation • Salinisation or salt water intrusion • Habitat loss • Poor climatic conditions • Flooding	• Surface soil erosion • Heavy metal or aluminium toxicity • Soil organic matter decline • Sodic or saline subsoil • Pesticide, herbicide and nutrient leaching • Pesticide, herbicide and nutrient runoff • Pests, weeds and diseases	• No subsurface drainage • Subsurface drainage (ag pipe) • Flood mitigation works (levee banks) • Subsoil levelling • Shallow drains (spoon drains) • No irrigation • Spray irrigation • Trickle irrigation • 0-1ML/ha per irrigation • Irrigation from surface water • Deep ripping • Cutter bar • Tyne plough or chisel plough

Identifies system attributes and distinguishes them from SIs.
Although not evident in the framework sample above, system attributes are identified: soil; climate; and vegetation. These attributes are distinguished from hazards (indicators of unsustainability).

Identifies system processes and distinguishes them from SIs.
Although not evident in the framework sample above, possible sugarcane farm management practices are identified: irrigation; cultivation; fertiliser application; width of riparian zone etc. Some of these practices are processes, such as irrigation, cultivation, and fertiliser application. These processes are distinguished form hazards (indicators of unsustainability).

Identifies SIs that gauge system processes and different aspects of each attributes.
Relationships between management practices and system attributes are delineated as potential hazards to sustainability (e.g. waterlogging). As suggested above, these hazards

can be regarded as indicators of unsustainability. These indicators highlight potential problems, but do not show the state or direction of system attributes and processes, which is the typical function of SIs.

Structures SIs according to spatial scales.
Hazard indicators are not structured according to spatial scale; they are applicable to only the field scale.

Identifies system capacity by proposing threshold values for system attribute and process SIs.
System capacity is inherently addressed by the identification of suitable land management practices: land management practices that do not exceed the capacity of a field are promoted.

Illustrates balance between states of SIs.
Hazards (unsustainability indicators) have two states; present and absent: a hazard can be present for a land unit, or absent. For example, for land unit 1127 hazard 'soil acidification' is present, but hazard 'pests, weeds, and diseases' is absent. The structure of this framework does not allow an illustration of balance between states of hazards: only 'present' hazards are displayed.

Other Benefits / Drawbacks
The relationships between management practices and land attributes are delineated as potential hazards to sustainability (e.g. waterlogging). These hazards can be made spatially explicit when linked with a GIS.

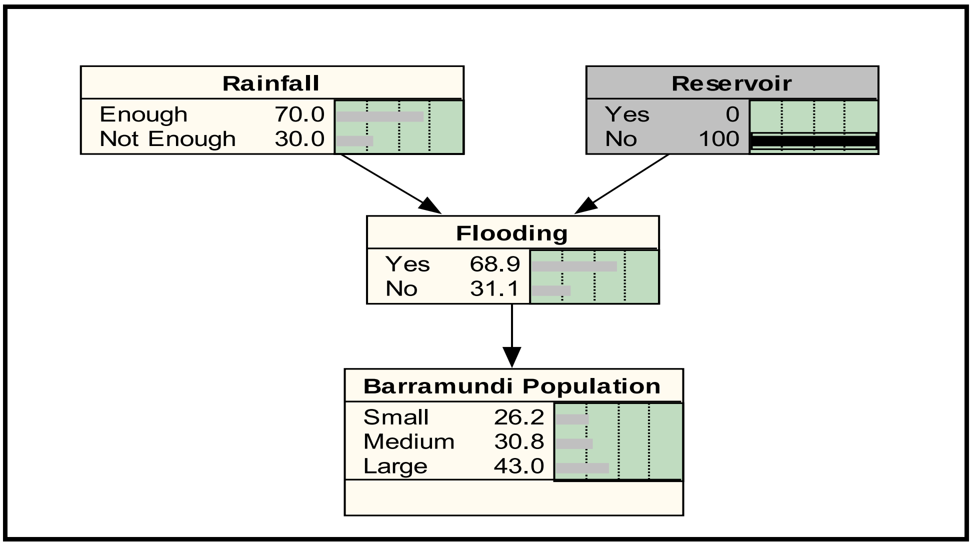
Management actions in the form of Best Management Guidelines are prescribed for land units according to possible hazards. Hazards are considered to be either reversible or irreversible. Reversible hazards are grouped into short term (<5 years), medium term (5-25 years), and long term (>25 years). This framework collates information on land attributes, management actions, hazards, and reversibility of hazards to form a resource planning framework which can be used to define the conditions for the use of land to ensure that farm production and environmental health are sustainable.

4.8 Bayesian Belief Networks

A Bayesian Belief Network (BBN) is a conceptual representation of a system in the form of a cause and effect diagram. A BBN is founded on boxes and arrows: boxes represent variables and arrows represent the flow of cause and effect (Figure 4.3). Each variable has a number of states (eg. yes/no, low/medium/high). Each state has a probability of occurrence. Probabilities for all states of each variable add to 100%. The relationship between two variables determines their states' respective probabilities of occurrence. The information that describes each relationship is stored within a conditional probability table (Table 4.7). The network is an interconnected system: change in one variable generates changes in other variables. This framework is therefore used to understand the likelihood of an outcome given the state of variables which influence the outcome.

According to the fictitious conceptual model shown in Figure 4.4, rainfall and the presence/absence of a reservoir affect whether a flood occurs, which in turn affects the population size of Barramundi in the river. Figure 4.4a illustrates the expected population size of Barramundi given enough rainfall and no reservoir. Figure 4.4b shows the change in population size of Barramundi given the presence of a reservoir. Clearly, the presence of a reservoir increases the likelihood of a small Barramundi population.

a)



b)

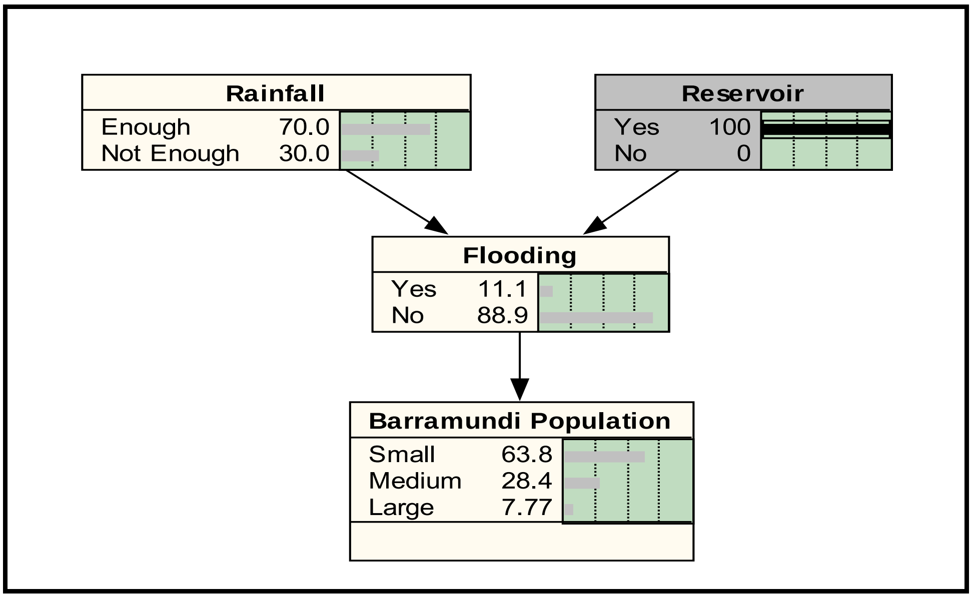


FIGURE 4.4
A BBN SHOWING EXPECTED POPULATION SIZE OF BARRAMUNDI IN A RIVER AS A RESULT OF FLOODING IF A RESERVOIR IS (a) NOT PRESENT and (b) PRESENT

Table 4.11 displays a conditional probability table for the variable ‘flooding’ shown in Figure 4.4 above. The states of the two variables, ‘rainfall’ and ‘reservoir’, determine the degree to which flooding is ‘yes’ or ‘no.’

TABLE 4.11
CONDITIONAL PROBABILITY TABLE DESCRIBING HOW RAINFALL AND RESERVOIR AFFECT FLOODING

Rainfall	Reservoir	Yes (Flooding)	No (Flooding)
Enough	Yes	15	85
Enough	No	95	5
Not Enough	Yes	2	98
Not Enough	No	8	92

Identifies system attributes and distinguishes them from SIs.
System variables, expressed as boxes, are considered to be SIs. System attributes are not clearly identified or distinguished from SIs. For example, the SI 'Barramundi Population' refers to 'population size', but 'Barramundi Population' is not explicitly identified as a system attribute.

Identifies system processes and distinguishes them from SIs.
System processes are not clearly identified or distinguished from SIs. For example, the SI 'Flooding' is itself a process, but this is not clearly stated.

Identifies SIs that gauge system processes and different aspects of each attributes.
System attributes and processes are gauged by SIs. A number of SIs can be used to gauge different aspects of system attributes and processes. For example, the system process 'Flooding' can be gauged with two SIs: Frequent Flooding; and Flood Height. Another example: the system attribute 'Barramundi Population' can be gauged with three SIs: Population Size; Disease Outbreak; and Average Fish Size.

Structures SIs according to spatial scales.
There is no straightforward way to structure SIs according to spatial scales. When building a BBN, a particular spatial scale may be in mind (e.g. farm), and variables used will reflect this scale.

Identifies system capacity by proposing threshold values for system attribute and process SIs.
A BBN SI does not use threshold values: realised SI values are not compared with desired SI values. Rather than assess sustainability, a BBN is used to understand the likelihood of an outcome given the states of SIs which influence the outcome. In essence, a BBN is a 'scenario testing tool' rather than a 'sustainability checking tool.'

Illustrates balance between states of SIs.
Bar columns and percentage values are used to illustrate balance between states of SIs. For example, in Figure 4.4b percentages (68.3%, 28.4%, 7.77%) and bar columns (long, medium length, short) illustrate balance between states (small, medium, large) of the SI 'Barramundi Population.'

Other Benefits / Drawbacks
Rather than distinguish process SIs from attribute SIs, BBNs distinguish higher order SIs from lower order SIs by establishing a flow of cause and effect: higher order SIs cause effects in lower order SIs. The identification of causes and effects facilitates understanding of system relationships.

Temporal dimension can be built into a BBN by creating a series of static BBNs which represent the system at different points in time (Wooldridge 2003). Inferred beliefs of previous time steps are used to estimate beliefs in current and future time steps (Wooldridge

2003). Replicating BBNs to incorporate temporal dimension results in large and complex networks that require considerable time and resources to develop (Wooldridge 2003).

BBNs have the following benefits:

- A useful tool for structuring and analysing decision problems (Robertson & Wang 2004);
- Allow the integration of scientific and experiential knowledge (Cain et al 1999);
- Account for risks and uncertainties in the decision making process (Robertson & Wang 2004);
- Have a highly visual and transparent model structure that facilitates the engagement of stakeholders (Wooldridge 2003); and
- Have been effectively applied to examine the impacts of planning and management options on natural resource systems (Cain et al. 1999; Robertson & Wang 2004; Mc Neill & MacEwan 2004).

4.9 AMOEBA

AMOEBA is the Dutch acronym for "a general method of ecosystem description and assessment." It is a visual tool, originally designed to capture the sustainability of marine ecosystems (Figure 4.5). Ten Brink et al. 1991 propose that it is a conceptual model for the development of quantitative and verifiable ecological objectives, which can be used to describe and test ecosystems for sustainability. The development of an AMOEBA involves setting a reference condition that represents the natural state of a given ecosystem. This natural state is assumed to be sustainable and the further the system departs from this state, the less sustainable it becomes.

The AMOEBA in Figure 4.5 presents the sustainability of a tidal ecosystem. The arms of the AMOEBA depict the abundances of seagrass, tiger prawns, sand worms, and mangroves. The reference condition, depicted by the circle, is the ideal population size of each species in an ecosystem in a natural state. An intersection between the circle and an AMOEBA arm, if present, indicates the reference condition has been met or exceeded. The tiger prawn population size is viewed as ideal because the arm meets with the reference condition circle. If an arm falls short of the circle, the respective population size is too small (seagrass and mangroves). If an arm extends beyond the circle, the population size is too large (sand worms). It appears that this tidal ecosystem is not sustainable.

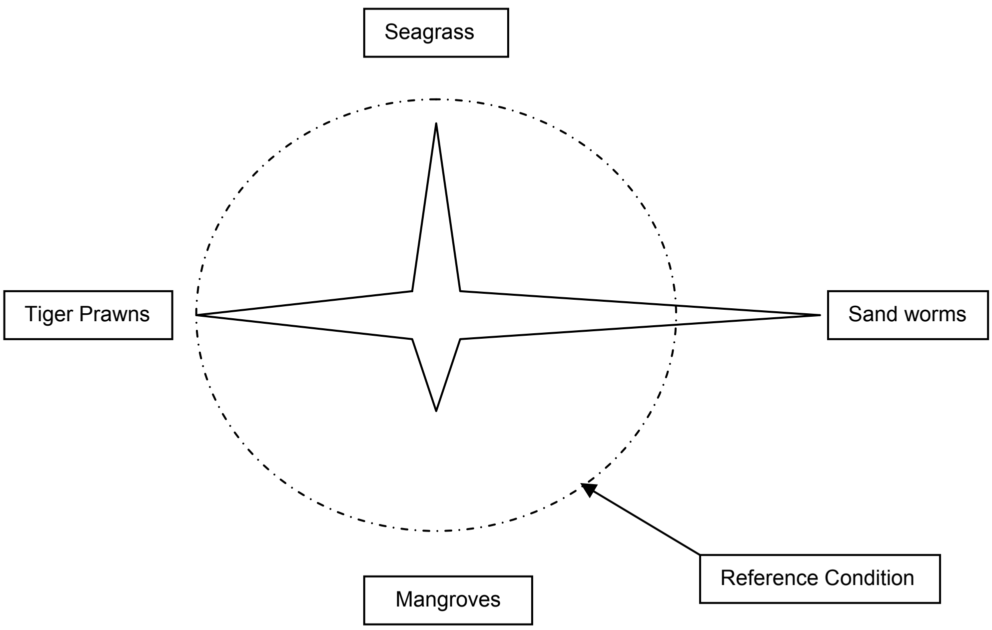


FIGURE 4.5
AN AMOEBA PRESENTING THE SUSTAINABILITY STATUS OF A TIDAL ECOSYSTEM

This method has been severely criticised by Bell & Morse 1999 and Rennings & Wiggering 1997, on grounds including the following:

1. The AMOEBA is based on population sizes and therefore does not provide information on interactions within an ecosystem;
2. All indicators are combined into one diagram to present overall sustainability – the accumulation of indicators' states to approximate overall sustainability is viewed as being too simplistic; and
3. Identifying an ecosystem's natural state is difficult.

Bell & Morse 1999 propose a modified version of the AMOEBA for sustainability analysis. Changes to the original AMOEBA are listed in Table 4.12. Irrigation SIs are used in modified AMOEBAs in Figures 4.6 and 4.7.

TABLE 4.12
SUGGESTED AMOEBA MODIFICATIONS BY BELL & MORSE 1999

SIs such as salt balance and healthy soil replace species populations.
Replace reference conditions with threshold ranges. A range is created with two circles instead of one. The inner circle depicts the lowest acceptable value for a SI and the outer circle depicts the highest acceptable value for the SI.
Threshold range values are determined by using existing guidelines (eg. Australian and New Zealand Guidelines for Fresh and Marine Water Quality), stakeholder opinion, or scientific advice.
The zone between the concentric circles is depicted as sustainable, while the area outside this zone is unsustainable.

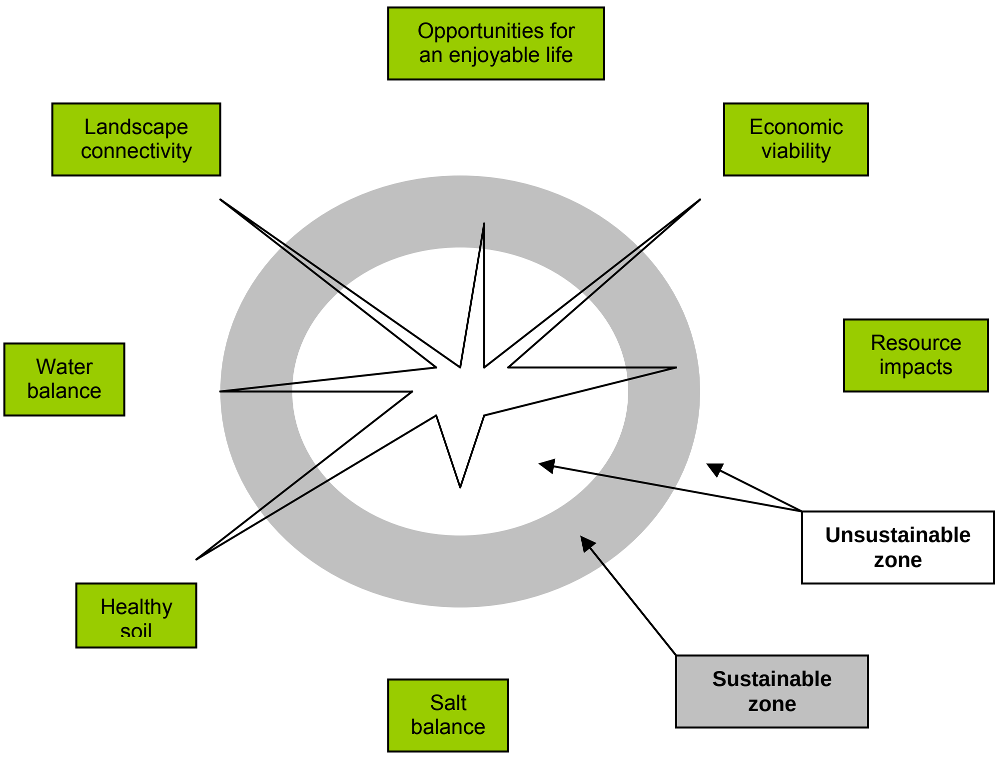


FIGURE 4.6
AN AMOEBA REPRESENTING THE SUSTAINABILITY OF A FICTITIOUS IRRIGATION AGROECOSYSTEM AT THE CATCHMENT SCALE

Some aspects of the irrigation system shown in Figure 4.6 are sustainable (eg. Resource Impacts and Opportunities for an Enjoyable Life), one aspect is marginally sustainable (e.g. Water Balance), while others are unsustainable (eg. Salt Balance and Landscape Connectivity).

Separate AMOEBAs can be constructed for each of the SIs shown in Figure 4.6. This allows us to identify factors, or lower level SIs that determine the values assigned to the higher level SIs. For example, lower level SIs used to inform *Water Balance* (SI in Figure 4.6) are displayed in the AMOEBA in Figure 4.7.

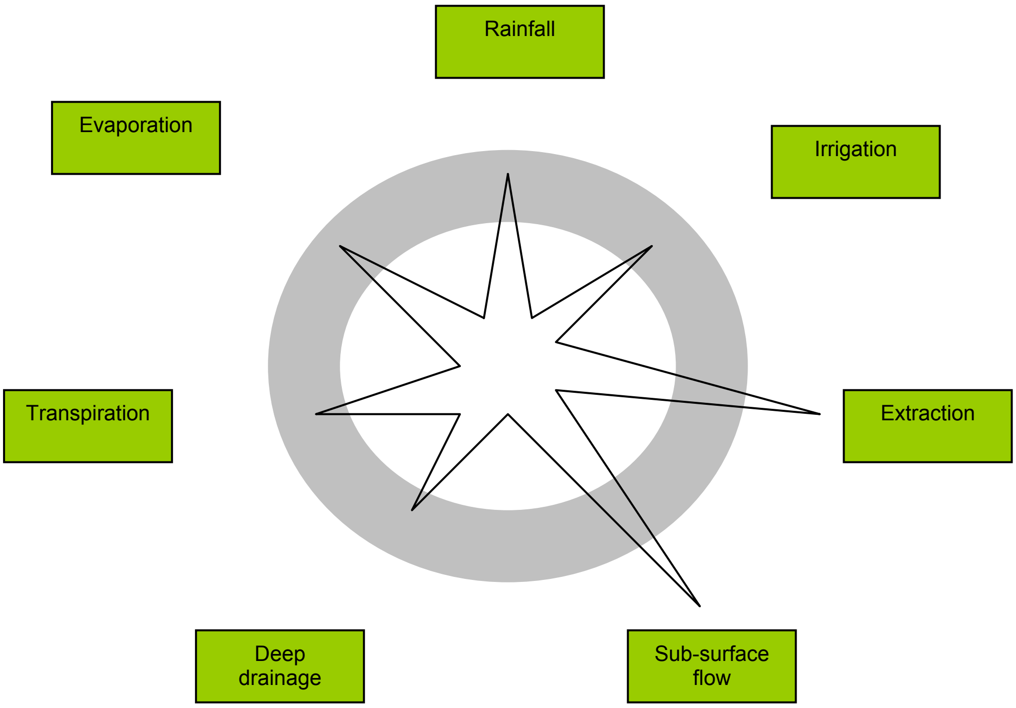


FIGURE 4.7
AN AMOEBA REPRESENTING WATER BALANCE INDICATORS FOR A FICTICIOUS IRRIGATION SYSTEM AT THE CATCHMENT SCALE

This AMOEBA indicates that the flow of sub-surface groundwater is too high. However, if extraction of groundwater, shown in the figure to be too high, prevents groundwater accumulation, then overall the water balance is sustainable. This assessment can then be transferred to the overall sustainability AMOEBA presented in Figure 4.6.

Identifies system attributes and distinguishes them from SIs.
System attributes are not clearly identified or distinguished from SIs. For example, the SI ‘Healthy Soil’ refers to soil, but ‘Soil’ is not explicitly identified as an attribute.

Identifies system processes and distinguishes them from SIs.
System processes are not clearly identified or distinguished from SIs. For example, the SI ‘Irrigation’ is itself a process, but this is not clearly stated.

Identifies SIs that gauge system processes and different aspects of each attribute.
AMOEBA is an empty SI framework. Therefore, any number and combination of SIs, regardless of whether they are process SIs or attribute SIs, can be included. For example, in

Figure 4.7 SIs gauge seven different ‘Water Balance’ related processes. Similarly, attribute SIs (e.g. pH, turbidity) that gauge different aspects of ‘Water Quality’ could be used to construct an AMOEBA.

Structures SIs according to spatial scales.
SIs are not structured according to spatial scales. SIs that are relevant to a common spatial scale can be grouped to form a scale specific AMOEBA.

Identifies system capacity by proposing threshold values for system attribute and process SIs.
Axis scales of reference can be added to the arms of the AMOEBA to give meaning to their length and allow the incorporation of the upper and lower threshold values. For example, the AMOEBA arm representing deep drainage in Figure 4.6 could be scaled to depict depth of water draining in millimetres per day (mm/day). If 4 – 10mm/day was decided to be the threshold range, then 3mm/day would be depicted by an arm that falls short of the sustainable zone and 15mm/day would be depicted by an arm that extends beyond the sustainable zone.

Illustrates balance between states of SIs.
There are two SI states is this form of the AMOEBA: sustainable; and unsustainable. The length of an AMOEBA arm shows the state of a SI. A number of arms are shown to illustrate balance between states of SIs.

Other Benefits / Drawbacks
When organised hierarchically, SIs help us build a range of AMOEBAs at different levels of organisation. This process facilitates the understanding and visualisation of sustainability. In essence, AMOEBA is a presentation tool particularly suited to involving stakeholders in identifying indicators, setting threshold values, and making sustainability assessments.

5. Assessment Criteria for Sustainability Indicator Frameworks

The criteria used to analyse the SI frameworks are reviewed in this section. This review is undertaken to develop a refined set of criteria, which will be used in the next section to assess and score each SI framework.

If initial criteria are deemed useful they are either *retained* or *modified*. If deemed not useful, they are *rejected*. Table 5.1 presents a verdict (*retained, modified,* or *rejected*) for each of the initial criteria. These verdicts are explained below.

TABLE 5.1
REVIEW OF CRITERIA USED TO ANALYSE THE SUSTAINABILITY INDICATOR FRAMEWORKS

Criteria	Verdict
1. Identifies system attributes and distinguishes them from SIs.	Reject
2. Identifies system processes and distinguishes them from SIs.	Reject
3. Identifies SIs that gauge system processes and different aspects of each attribute.	Reject
4. Structures SIs according to spatial scales.	Modify
5. Identifies system capacity by proposing threshold values for system attribute and process SIs.	Modify
6. Illustrates balance between states of SIs.	Retain

Criteria 1 & 2
Criteria 1 and 2 suggest that system attributes and processes should be identified and distinguished from SIs. There are two alternative explanations why none of the reviewed SI frameworks do this: i) A SI framework **is not** made more useful by the explicit identification of system attributes and processes: the elucidation of system attributes and processes does not improve understanding of what SIs gauge or should gauge; or ii) A SI framework **is** made more useful by the explicit identification of system attributes and processes, but this step has been overlooked to date.

We suggest that conceptual models are useful for identifying, illustrating, and contextualising system attributes and processes. From these models it is more obvious which parts (attributes and processes) of a system should be gauged. Therefore, we suggest that conceptual models should be used to guide the development of SIs; **a SI framework does not need to explicitly identify system attributes and processes**. However, when a SI framework is presented, it should be complemented with a conceptual model to show which system elements are gauged with the proposed SIs. In consideration of this review, criteria 1 and 2 are rejected.

Criteria 3
Criteria 3 proposes that a range of SIs is needed to gauge an attribute and a process. This criteria assumes that all attributes and processes should be gauged with certain numbers of SIs. Such a rigid approach may impede the development and selection of SIs by stakeholders. Criteria 3 is rejected for this reason.

Criteria 4
Some SI frameworks structure SIs according to spatial scales. Some SI frameworks can be developed for a number of spatial scales: the same SI framework structure, but different SIs are used for different spatial scales. Both ways allow a system to be reviewed at a range of spatial scales. Criteria 4 is modified to become the following criteria: **Can be used to review systems at a range of spatial scales.**

Criteria 5
Not all threshold values are decided on the basis of system capacity. In some cases, stakeholders may select a threshold value that maybe desirable, regardless of whether it represents system capacity or not. Criteria 5 is modified to become the following criteria: **Incorporates or allows the incorporation of SI threshold values.**

Criteria 6
SI frameworks were found to be more useful for presenting sustainability assessments when they provided a chart, diagram, or table to illustrate SIs states. Criteria 6 identified this and is therefore retained: **Illustrates balance between states of SIs.**

In the previous section, analyses identified other useful traits of SI frameworks:

- Identifies specific relationships between SIs;
- Uses hierarchy to promote system thinking and assist in SI selection;
- Facilitates participatory research;
- Integrates scientific and experiential knowledge; and
- Simulates and tests planning and management scenarios.

These traits are combined with the modified and retained criteria identified above to form a list of refined criteria for assessing SI frameworks.

6. Sustainability Indicator Framework Assessment

The refined criteria developed in the previous section are used to assess the nine SI frameworks presented in this document. Table 6.1 describes this assessment. Table 6.2 illustrates this assessment and assigns scores to each SI framework. High scores suggest high usefulness, low scores suggest low usefulness.

TABLE 6.1
REFINED CRITERIA FOR ASSESSING SI FRAMEWORKS

Refined Criteria	Assessment
1. Incorporates or allows the incorporation of SI threshold values.	SI frameworks that integrate threshold values with SIs, announce that there are desired states for system attributes and processes. If a SI threshold value is exceeded, then the respective system attribute or process must be managed to improve its state. Some SI frameworks, such as Risk Assessment Triggers, clearly outline threshold values. Others, such as AMOEBA, allow the incorporation of threshold values.
2. Illustrates balance between states of SIs.	Refer to page 13, criteria 6. Bayesian Belief Networks and AMOEBA both provide ways to illustrate balance between states of SIs.
3. Identifies specific relationships between SIs.	SI frameworks that identify specific relationships between SIs improve our understanding of causes and effects. The following SI frameworks all perform this function: State & Control; Driving Force, State, and Response; Bayesian Belief Networks and TIM.
4. Uses hierarchy to promote systemic thinking and assist in SI selection.	Hierarchy is an important feature of SI frameworks, because it gives context for relationships between SIs. With hierarchy, SI frameworks inform us how the inclusion/exclusion of SIs improves/degrades the sustainability assessment method. With hierarchy, a SI framework is more representative of a system, because it shows connectivity between framework elements. This improves our understanding of system function, which allows the selection of SIs that more appropriately gauge sustainability. Bayesian Belief Networks and AMOEBA use hierarchy.
5. Can be used to review systems at a range of spatial scales.	A SI framework that can be applied at a range of spatial scales is more flexible and provides outputs for a broader range of stakeholders. For example, farmers may be interested in farm and field scales, whereas policy makers may be interested at other scales, such as catchment and regional. Most SI frameworks can be applied at a range of scales, however some cannot, because they either prescribe SIs that are scale-specific (eg. Driving Force, State and Response), or are designed for a specific scale (eg. Threat Identification Model).
6. Facilitates participatory research.	Unlike other SI frameworks, AMOEBAs and Bayesian Belief Networks don't prescribe SIs: they provide structures that can help users build their own 'world views' using SIs. An 'empty' structure provides opportunities for stakeholders to be involved in SI selection. For this reason, AMOEBAs and Bayesian Belief Networks are particularly suited to the facilitation of participatory research.

7. Integrates scientific and experiential knowledge.	SI frameworks that are not wholly prescriptive allow the integration of experiential knowledge with scientific knowledge. By improving and updating knowledge, whether it be by absorbing experiential information or incorporating model outputs, SI frameworks become more comprehensive and accurate. Threat Identification Model, AMOEBA, and Bayesian Belief Networks are SI frameworks that allow, or are based on, the assimilation of experiential and scientific knowledge.
8. Simulates and tests planning and management scenarios.	SI frameworks with scenario simulation capability are useful for developing and selecting planning strategies and management actions. TIM and Bayesian Belief Networks have this capability.

TABLE 6.2
ILLUSTRATION OF SI FRAMEWORK ASSESSMENT

	SUSTAINABILITY INDICATOR FRAMEWORKS								
Criteria	**State & Control**	**Driving Force, State & Response**	**Condition & Trend**	**System Division**	**Sustainability Criteria**	**Threat Identification Model**	**Risk Assessment Triggers**	**Bayesian Belief Networks**	**AMOEBA**
1	■	■	■	■	■		■		■
2			■				■	■	■
3	■	■						■	
4								■	■
5	■	■	■	■	■			■	■
6								■	■
7						■		■	■
8						■		■	
Score	**3**	**3**	**3**	**2**	**2**	**2**	**2**	**7**	**6**

CRITERIA KEY

1. **Incorporates or allows the incorporation of threshold values**
2. **Illustrates balance between states of SIs**
3. **Identifies specific relationships between SIs**
4. **Uses hierarchy to promote systemic thinking and assist in SI selection**
5. **Can be used to review systems at a range of spatial scales**
6. **Facilitates participatory research**
7. **Integrates scientific and experiential knowledge**
8. **Simulates and tests planning and management scenarios**

Bayesian Belief Networks scored the highest: with 7 out of 8. AMOEBA scored the second highest: with 6 out of 8. Based on these results these SI frameworks are probably the most useful for progressing development of the NAIF Sustainability Framework.

7. Recommendations

To progress development of the NAIF Sustainability Framework, the following recommendations are made:

1. Adopt the AMOEBA SI Framework to accomplish the following: facilitation of SI development; facilitation of threshold setting; presentation of sustainability assessments; and facilitation of stakeholders' understandings of sustainability.

2. Adopt Bayesian Belief Networks to simulate and test planning and management scenarios.

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9. Glossary

Equity	The quality of being fair or impartial
Framework	A method or scheme of classification used to structure information
Indicator	A parameter, with a range of values, that gauges a system attribute or process, thereby signaling a particular condition or trend
Irrigation Agroecosystem	A system that includes ecosystems and irrigation farming systems. Attributes include the following: farmers; native vegetation; market price; and farming organizations. Processes include the following: irrigation; riparian rehabilitation; product trade; and information dissemination
Landscape	A land region with institutional, cultural, ecological, social, and economic systems continuously interacting through processes that operate at a range of spatial and temporal scales
System Attribute	A part of a system that is subjectively defined. Different attributes are present at different spatial scales. For irrigation agroecosystems, farm scale attributes include the following: groundwater; crops; and pests. Catchment scale attributes include the following: river; native vegetation; and climate
System Process	An action that occurs over time. Irrigation agroecosystem processes include the following: rainfall; deep drainage, irrigation; harvesting; runoff; and product transport
System	A dynamic structure that comprises interacting attributes and processes
Sustainability	A process that involves designing, developing, monitoring, evaluating and modifying a system to ensure that its attributes and processes are desirable as decided by stakeholders
Sustainability Indicator Framework	A structure of sustainability indicators usually proposed as a tool for assessing the sustainability of a system

Appendix 1. Sustainability Indicators which can be used to Assess Aspects of the Biophysical Sustainability of Irrigation Agroecosystems at Field, Farm, District, Scheme, and Catchment Scales.

Categories	Indicators	
Healthy Soil	• nutrient balance • soil salinity • soil sodicity • pH • exchangeable aluminium content • soil loss • soil compaction • soil organic matter • soil fertility • artificial N requirements • artificial P requirements • total phosphorus • DTPA trace elements • % bare soil • soil water holding capacity • dispersive nature • physical barriers to root development • number of earthworms per soil unit	• soil consistence • soil texture • soil colour • water intake rate • soil strength • slaking and dispersion • cotton strip assay • total nitrogen • sodium bicarbonate ($NaHCO_3$ P) • exchangeable K and Na • effective root depth • potential for leaching of acid sulphates, salt, and nutrients • depth to water table • % clay • depth of topsoil • nutrient availability • microbiological diversity
Physical Water Resources	• access to surface water / groundwater • availability of surface water / groundwater • seasonality of surface water and groundwater availability • water supply system reliability • water supply system reversibility • maximum water abstraction rate • depth to water table	• source water salinity, sodicity and pH • salt, nutrient and pesticide concentrations • water supply system vulnerability • equity in water sharing • water use efficiency • demand as % of available aquifer and surface water volumes • spatial distribution of surface waters and groundwater
Farming and Irrigation Methods	• matching crop requirements with water application • daily, schedule, and annual water application rates • extent and duration of ponding • surface water runoff volume • % of crop land with reduced tillage and stubble retention • weather forecasting used to plan chemical applications • pesticide application in grams of active ingredients according to toxicity • method of tillage • management of chemical residues • nutrient balance • implementation of best management practices	• crop rotation frequency • fallow frequency • % of farm area under fallow • % of farm area with low input crops • water stored in root zone as % of irrigation water applied • agrichemicals and fertilisers used per quantity of crop produced • % of irrigation water supplied by tail water • sprinkler, low level sprinkler, micro, drip, subsoil, high rate sprays, or flood irrigation • frequency of fertiliser applications • application of soil conservation measures • chemical residue levels in produce • net volume of water extraction

	• frequency of pest control • overall consumed ratio (water)	• field application ratio (water)
Site Design	• site risk of runoff • average width of buffer zones between farmland and sensitive rivers, streams, lakes, and/or wetlands	• extent of surface drainage • length of farmland edge bordering with native vegetation • plan approval
Water Service Provision	• supply reliability • cost per ML • agreed service level • conveyance ratio • dependability of irrigation duration • effectiveness of infrastructure • relative change of water level	• water supply system reversibility • water supply system vulnerability • water delivery performance • distribution ratio • dependability of irrigation interval • discharge ratio
Landscape Integrity	• length of farmland edge bordering with native vegetation • rates / loads of sediment, nutrients, salt and pesticides passing to surface waters • concentration of sediment, nutrients, salt and pesticides in surface waters • depth to water table • net salt accumulation / leaching • distance between farmland and sensitive rivers, streams, lakes, and/or wetlands • average width of buffer zones between farmland and sensitive rivers, streams, lakes, and/or wetlands • gully erosion index • number of new reports of new pests and weeds • level of farmland encroachment onto floodplain • habitat and food source value of site for native fauna • ratio of land use capacity to current land use • dust storm frequency • algal bloom frequency • frequency of river discontinuity • vegetated stream length • number of access ways through riparian vegetation for stock • stream sinuosity • % habitat loss per year	• extent of bare soils • extent of remnant vegetation • rates / loads of nutrients, salt and pesticides leaching to groundwater • concentration of nutrients, salt and pesticides in groundwater • extent of cultivated area • extent of forested area • area of weeds • extent of salt pans • extent of sodic soils • extent of saline soils • extent of crop dieback • crop diversity • extent of buffer strips and wildlife corridors • soil loss per year • land slope • distance between farmland and national parks • in-stream invertebrates, fish, frogs, water birds population sizes and diversity • population sizes of feral animals • presence of fauna of high conservation value • enterprise diversity • change in area of productive agricultural land • fish kill frequency • number of river structures • % catchment cleared, native vegetation • % of waterways fenced • AUSRIVAS survey ratings
Climate	• frequency of cyclones and storms with potentially damaging winds • seasonality of rainfall	• flooding frequency • median annual rainfall

Appendix 2. A Summary of Key Documents Relating to Indicators, Indicator Frameworks, and Sustainable Agriculture

Reference	Sustainability Indicator Framework	Number of Biophysical Indicators	Number of Socio-economic Indicators	Scales	Notes
Walker, J. & Reuter, D.J. 1996 Indicators of catchment health – A technical perspective. CSIRO Publishing.	Condition & Trend	20	9	field farm	This book presents a series of indicators that can be used to assess the health of Australian catchments. A report card framework is used to structure the indicators. Threshold values are proposed for all indicators. Indicators are dived into two categories 1. Condition; and 2. Trend.
Muller, S. 1998. Evaluating the Sustainability of Agriculture - Reventado River Watershed Costa Rica.	Sustainability Criteria	32	17	field farm catchment	This report presents an assessment of agricultural sustainability at plot, farm, and watershed scales for the Reventado River Watershed. A sustainability index is derived for each farm and recommendations to improve sustainability are presented. Sustainability criteria divided into the following categories: 1. Productivity; 2. Efficiency; 3. Resilience; 4. Rules for resource management; and 5. Biodiversity.
Walker, J., Veitch, S. 1997. Assessment of Catchment Condition in Australia's Intensive Land Use Zone: A biophysical assessment at the national scale. Final Report for the National Land and Water Resource Audit.	System Division	21	0	catchment	This report presents an assessment framework for catchment health based on a systems model of catchment function and a model of catchment condition. Indicator selection criteria are proposed.
SCARM 1998. Sustainable Agriculture: Assessing Australia's recent performance. CSIRO Publishing, Melbourne.	System Division	9	10	catchment	Indicators to assess the sustainability of Australian agriculture are divided into the following categories: 1. Long-term real net farm income; 2. Natural resource condition; 3. Off-site environmental impacts; 4. Managerial skills; and 5. Socio-economic impacts.

Department of Primary Industries and Energy Bureau of Rural Resources 1991. Environmental Indicators for Sustainable Agriculture. Report on a National Workshop.	-	30	9	local regional national	This book is a series of articles including information papers, position papers, discussion papers, and summaries. These were presented at a national workshop formed to report on the ecological sustainability of agriculture in Australia. Six groups were established to represent the major agricultural systems and regions within Australia. Indicators were generated for each of these systems. The groups are listed: 1. Rainfed crop and animal production (8 1st order indicators); 2. High rainfall, permanent pasture animal production (7 1st order indicators); 3. Low rainfall, rangeland animal production (4 1st order indicators); 4. Irrigated agricultural crops and pastures (11 1st order indicators); 5. Intensive horticulture/viticulture (with and without irrigation) (6 1st order indicators); and 6. High rainfall tropical agriculture (3 1st order indicators).
Bell, S., Morse, S. 1999. Sustainability Indicators – Measuring the Immeasurable. Earthscan Publications Limited, London.	State & Control AMOEBA	-	-	-	Chapter 1 provides background on the issue of sustainability indicator development. Chapter 2 focuses on examples of single and multiple sustainability indicators. Chapter 3 looks at institutional sustainability indicators, sustainable cities, and introduces the notion of using sustainability indicators in projects. Chapter 4 sets out an alternative, systemic manner for the development of sustainability indicators. Chapter 5 describes the development of sustainability indicator development tools within project contexts. Chapter 6 sets out the systemic approach to sustainability indicator development stressing the essential participative nature of understanding sustainability. Chapter 7 focuses on setting out a number of further questions arising from the discussion, and provides an outline of future research interests.
OECD 1993. OECD Core Set of Indicators for Environmental Performance Reviews: A Synthesis Report by the Group on the State of the Environment.	Pressure, State, and Response	42	11	national / international	This report presents a core set of sustainability indicators for assessing environmental sustainability. The Pressure, State, and Response model is used to structure the sustainability indicators.
OECD 2002. Norwegian Institute of Land Inventory (NIJOS) and OECD Expert Meeting on Indicators of Agricultural Impacts on Landscapes.	Pressure, State, and Response	5	7	landscape	This report applied the Pressure, State, and Response sustainability indicator framework to assess impacts of agriculture on landscapes. Indicators are divided into categories: 1. Indicators of agricultural landscape structures; 2. Indicators of agricultural landscape functions; 3. Indicators of agricultural landscape management; and 4. Indicators of agricultural landscape values.

Department of Environment, Sport and Territories 1996. Australia: State of the Environment 1996. CSIRO Publishing: Melbourne.	Pressure, State, and Response	inland waters 46 land 62	inland waters 7 land 0	landscape	Indicators to assess the condition of inland waters are divided into the following categories: 1. Groundwater; 2. Human health; 3. Environmental water quality; 4. Surface water quality; 5. Physical change; 6. Biotic habitat quality; and 7. Effective management. Indicators to assess the condition of land are divided into the following categories: 1. Accelerated erosion and loss of surface soil; 2. Physical changes to natural habitats; 3. Hydrological imbalance; 4. Introduction of novel biota into native habitats and communities; 5. Nutrient and salt cycling; and 6. Soil and land pollution.
Cai, X., McKinney, D.C., Rosegrant, M.W. 2001. Sustainability Analysis for Irrigation Water Management: Concepts, Methodology, and Application to the Aral Sea Region. International Food Policy Research Institute, Washington.	System Division	2	2	basin	This report outlines an irrigation sustainability assessment framework for the Aral Sea Region. The following indicators are used: 1. Water supply system reliability, reversibility and vulnerability; 2. Environmental system integrity (health of aquatic and floodplain ecosystems, water quality, soil degradation); 3. Equity; and 4. Economic acceptability. The implementation of the analytical framework is also presented.
Ministry of Agriculture and Forestry. 1997. Indicators of Sustainable Irrigated Agriculture. Technical Paper No. 00/03.	System Division	total 63 recommended 10	total 3 recommended 2	farm	This is a New Zealand government report on sustainability indicators for irrigated agriculture. Sustainability indicators are developed to assess the following: 1. Irrigation effects on water sources; 2. Irrigation effects on receiving waters; 3. Irrigation effects on soils; and 4. Effects of using wastewater for irrigation.
Sinclair Knight Merz 2004. Land Use Suitability and Capability for Irrigation Development. Draft Irrigation Development Guidelines and Evaluation Criteria.	Risk Assessment Triggers	8	9	farm	This paper, prepared by SKM for the MDBC, presents guidelines for sustainable irrigation development. Site suitability assessment is discussed in terms of an evaluation process and the roles of participating parties. Evaluation criteria and triggers for irrigation development (indicators and thresholds) are documented. This information is used to assess potential irrigation development sites. If the assessment deems the site "suitable", a site management plan and a site use license are drawn up. Thresholds are classified in terms of risk.

Johnston, R. 1998. Foresighting sustainable irrigation and river health. Australian Centre for Innovation and International Competitiveness and Agtrans Research. Canberra Land and Water Resources.	-	-	-	national	This booklet identifies future scenarios for the use and management of Australia's natural resources and considers implications of these scenarios for changes in the value, condition and frameworks for sustainable management. The process of foresighting is adopted to deliver future scenarios.
Rural Industries Research and Development Corporation 1997. Sustainability Indicators for Agriculture – Introductory Guide to Regional/National and On-Farm Indicators.	System Division	farm 10 regional national 7	farm 9 regional national 22	farm regional national	This book provides information on two types of sustainability indicators: • Those relevant to regional/national policymaking; and • Those relevant to on-farm management decisions. The framework groups indicators into the follow categories: 1. Profitability; 2. Land and water quality to sustain production; 3. Managerial skills; and 4. Off-site environmental impacts.
Department of Natural Resources and Environment 2001. Victorian Catchment Indicators 2001: our commitment to reporting on catchment condition.	System Division	24	6	catchment	This document sets out a program, based on a framework of sustainability indicators, to monitor the condition of Victorian catchments. Indicators are grouped into themes: 1. Socio-economic setting; 2. Land; 3. Waterways; 4. Managing Water; and 5. Biodiversity.
United Nations 1996. CSD Working List of Indicators of Sustainable Development. http://www.un.org/esa/sustdev/natlinfo/indicators/worklist.htm	Driving Force, State, and Response	20	6	regional national	This report outlines a framework of Driving Force, State and Response indicators. These groups of indicators are further divided into the following categories: 1. Social; 2. Economic; 3. Environmental; and 4. Institutional.