

Ecological Governance

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Abstract

Traditional approaches of planner-led technical decision making and process-led legal decision making in relation to addressing development impacts on ecological systems have been found to be inadequate when the sustainability limits are reached either in relation to providing resources for development or accommodating the adverse effects on ecosystems from development.

This paper sets out an approach of nested adaptive systems as the basis for governing and managing the integration of socio-economic systems with biophysical systems to reconcile development and ecosystem integrity.

The approach was applied to the development of the Canterbury Water Management Strategy. Rapid expansion of irrigation to convert dryland farms to dairying has led to the sustainability limits being reached for water availability, and for the cumulative effects of land use intensification on water quality and freshwater ecology. Traditional approaches to water management had failed to address this issue. A paradigm shift to systems thinking incorporating collaborative governance was fundamental to achieving a strategy supported by all stakeholders.

In the implementation of the strategy, it has also been demonstrated that managing to limits is insufficient. Rather, as a future development, a management approach based on nested adaptive systems incorporating collaborative governance is needed.

Introduction

When sustainability limits of resource availability and impacts of resource use are reached, an operational approach to sustainable development is needed. A nested adaptive systems approach to developing sustainability strategies for resource management is described. The application of this approach to water management in Canterbury, New Zealand, is summarised and compared to the strategy of increasing storage to meet projected water demand which had been proposed prior to the systems approach. The final section looks at the need to extend the use of nested adaptive systems to the management of ecosystems because the current approach of managing to limits is not sufficient to achieve sustainable management.

Systems Approach

The concept of sustainability as popularised by the Brundtland Commission [1] is given wide support but little guidance is given on how to make sustainability operational. This paper sets out a method of sustainability analysis based on nested adaptive systems as a basis for making sustainability operational.

The methodological framework is based on seven elements [2]:

- 1) the adaptive cycle of exploitation, accumulation, disturbance/release, and reorganisation for describing biophysical and socio-economic systems response to disturbance;
- 2) defining socio-ecological systems as linked adaptive cycles of biophysical and socio-economic systems;
- 3) specifying nested adaptive systems that operate at different spatial and time scales with linkages between the different scales;
- 4) identifying possible failure pathways which can lead to system collapse;
- 5) defining critical variables on possible failure pathways and thresholds associated with system collapse;
- 6) identifying potential management interventions to address failure pathways that could lead to system collapse; and
- 7) combining management actions at multiple scales of, and linkages between, biophysical and socio-economic systems into a sustainability strategy.

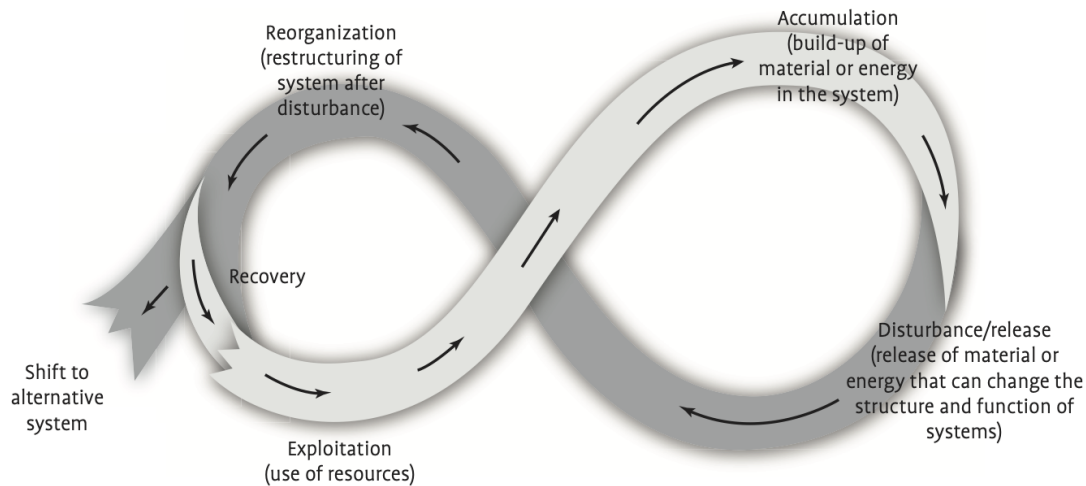
Adaptive Cycle

The framework is based on considering socio-ecological systems as nested adaptive systems. The first of the key elements is the “adaptive cycle” which describes biophysical and socio-economic systems in four phases [3]:

- Exploitation: the use of resources,
- Accumulation: the build-up of material or energy in the system,
- Disturbance/Release: a disturbance to the system that can cause release of material or energy and change the structure and function of the system, and
- Reorganisation: the restructuring of the system after disturbance.

The system response can be a recovery of the original system, or, a shift to an alternative system. The phases can be shown diagrammatically as a Lissajous figure (Figure 1).

This provides an operational basis for sustainability. Sustainability is the maintenance of the structure, function and relationships in adaptive cycles across different time and geographical scales. A key property for sustainability is “resilience” – the capacity of a system to absorb disturbance and still retain its basic function and structure.



Source: Adapted from Gunderson and Holling 2002

Figure 1 Adaptive Cycle [2]

Socio-Ecological Systems as Linked Adaptive Cycles

The second key element is considering socio-ecological systems as linked adaptive cycles (Figure 2) with a biophysical system linked to a socio-economic system. This figure shows four types of sustainability issues:

- The capacity of a biophysical system to adapt to disturbances that are independent of human activity (pathway 1 and the traditional study of ecological processes);
- The effects of the socio-economic system on the biophysical system (pathway 2 and the main emphasis of traditional environmental impact assessment);
- The effects of the biophysical system on the socio-economic system (pathway 3 which is receiving attention, on the negative side, through the resilience of communities to natural disasters, and on the positive side, through the ecosystem services that contribute to social well-being);
- The capacity of the socio-economic system to adapt to socio-economic disturbances (pathway 4 which includes issues like the recovery from the global financial crisis and the adequacy of institutional arrangements to implement management interventions).

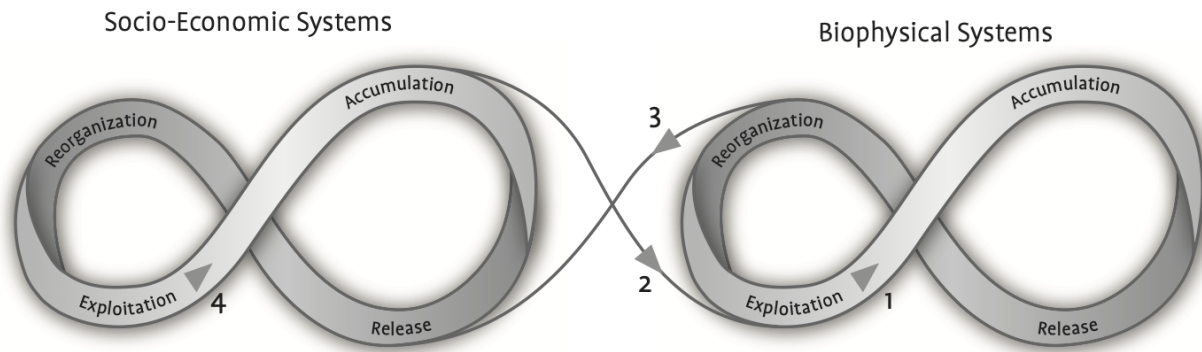


Figure 2 Types of Sustainability Issues [2]

Nesting of Adaptive Cycles

The adaptive cycles associated with different levels can be linked – what is referred to as “nested adaptive systems”. For example, for algal blooms in rivers there is a need to consider the catchment scale and the streambed scale. At the catchment scale the key phases are: (1) exploitation – the nutrient loss from land use intensification, (2) accumulation – the catchment load from the accumulation of nutrient losses from properties in the catchment, (3) release – the nutrient concentration in surface runoff and seepage to groundwater, (4) reorganisation – any attenuation of nutrients before flow reaches the streambed. At the scale of the streambed, the key phases for periphyton growth are: (1) exploitation – the nutrient levels, light availability and temperature for periphyton growth; (2) accumulation – the accrual period for biomass accumulation; (3) release – the occurrence of algal blooms, and (4) reorganisation – either recovery through the occurrence of freshes (flushing flows) to dislodge periphyton from the river bed or invertebrate grazing to reduce periphyton biomass, or, ongoing degradation with algal blooms. The linkage between scales and the nesting of adaptive cycles is shown in Figure 3 [2].

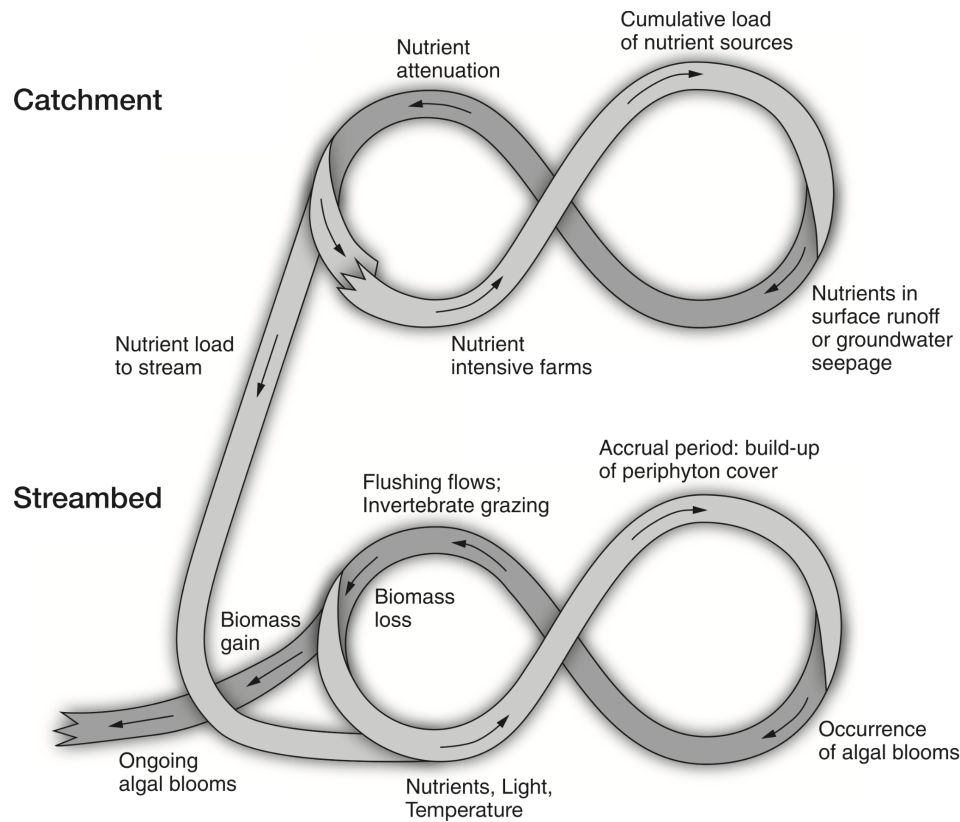


Figure 3 Nested Adaptive Cycles for Algal Blooms in Rivers [2]

Failure Pathways

A key aspect of the adaptive cycle is the potential for the system to fail and shift to an alternative degraded system. The processes leading to system failure are described as “failure pathways”. The processes leading to algal blooms in Figure 3 are an example of a failure pathway.

For Canterbury, the main failure pathways at different spatial scales are as follows:

- water availability at the regional scale where water demand exceeded supply;
- land use intensification at the regional scale leading to biodiversity loss;
- reliability of supply at the catchment scale for irrigation;
- cumulative effects on water quality and freshwater ecology at the catchment scale from increased nutrients;
- the reduction in flows in river reaches below environmental flow requirements at the subcatchment scale;
- inefficient irrigation at the property scale leading to excessive water use; and,
- poor land use practices at the property scale leading to diffuse discharges of water quality contaminants.

Critical Variables and Thresholds

For sustainability analysis of a nested adaptive socio-ecological system, priority needs to be given to the failure pathways that create the greatest vulnerability for system collapse. The critical variables and thresholds related to system change are the fifth key element of the framework.

For algal blooms, an example of a critical variable is the periphyton cover in streambeds. For benthic periphyton cover in streambeds, there are a number of thresholds defined in a three-tier framework for monitoring and management in relation to benthic cyanobacteria: (1) surveillance level of less than 20% coverage – with ongoing monitoring as the appropriate action; (2) alert level of 20 to 50% coverage with the response of public health authority notification, increased sampling frequency, and increased number of sites inspected; and (3) action level of 50% substrate coverage requiring public notification by media release, and public warnings to be erected at affected streambeds [4].

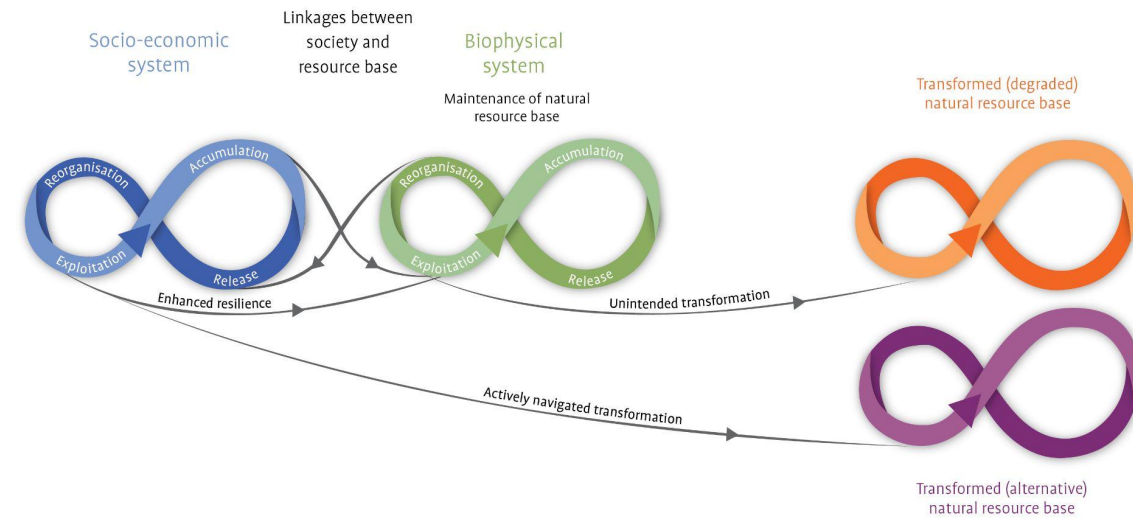
For regional water availability, the critical variable is whether water supply is sufficient to meet water demand. While at the property scale, it is the reliability of irrigation supply with an acceptability threshold typically of 85% availability of supply in the months of January and February – the months of peak irrigation demand in Canterbury [5].

Potential Management Interventions

The critical variables and associated thresholds become the targets for potential management interventions – the sixth key element of the framework. There are three generic outcomes for management interventions:

- No action (or inadequate action) leads to a degraded natural resource system;
- Action is taken to ensure that the threshold of change is not exceeded, and the natural resource system retains its structure and function (i.e. retains its sustainability); and
- Action is taken to transform the system to an alternative state that has a sustainable structure and function.

This is shown in Figure 4.



RESOURCE OUTCOMES FOR COUPLED SOCIO-ECONOMIC AND BIOPHYSICAL SYSTEMS

Figure 4 Resource Outcomes for Coupled Socio-Economic and Biophysical Systems

Sustainability Strategies

Management interventions in the biophysical system of water resources can occur at each of the phases of the biophysical adaptive cycle. These have been adapted from the stewardship strategies identified by Chapin and his colleagues [6]:

- Reducing the pressure on the resource (“reducing vulnerability” in Chapin’s terms) in the exploitation phase;
- Addressing the legacy issues of accumulated changes in the past (“enhancing adaptive capacity” in Chapin’s terms) in the accumulation phase;
- Increasing the resilience of the system to accommodate disturbance (“increasing resilience” in Chapin’s terms) in the disturbance/release phase;
- Rehabilitating the adverse effects of the system (“enhance transformability” in Chapin’s terms) in the reorganisation phase.

This can be shown diagrammatically as a Lissajous figure for interactions in the different phases of the biophysical system (Figure 5).

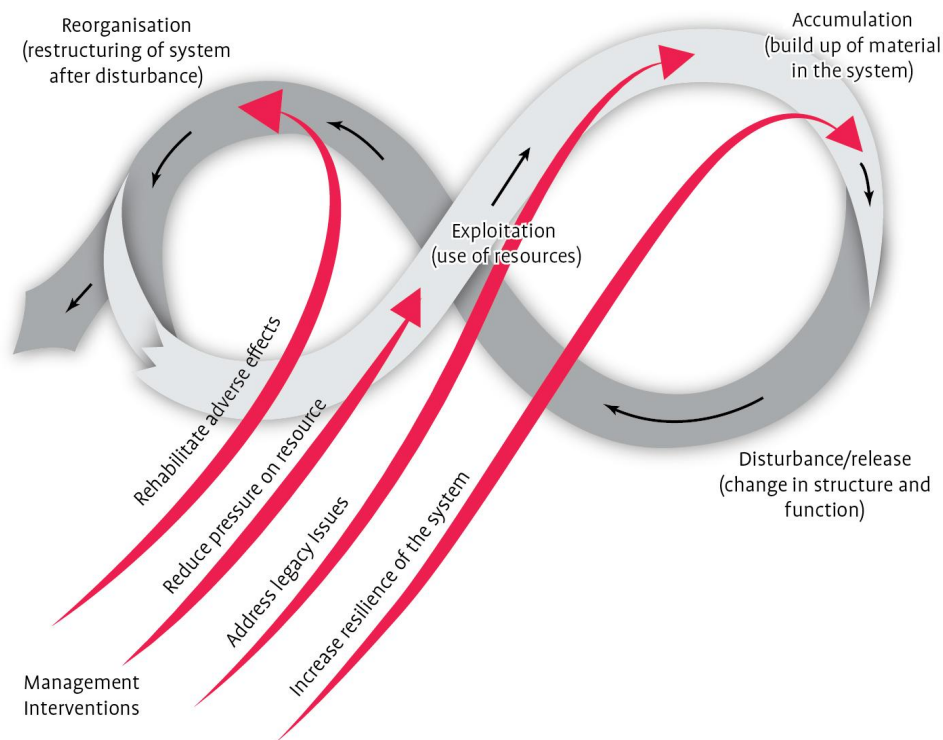


Figure 5 Management Interventions for each Phase of the Biophysical Cycle

To generate these management interventions, there is the need for a socio-economic process which can also be described as an adaptive cycle [2]:

- The use of human and economic resources for stakeholder, cultural and community engagement to consider how to collaboratively address the issue of sustainability of the water resources as well as the investment of technical resources to understand the issues and financial resources to undertake actions (i.e. exploitation phase).
- The accumulation of knowledge, social, cultural and economic capital to develop integrated approaches to sustainable strategies (i.e. accumulation phase).
- The formulation of new approaches to water management that change existing practices (i.e. disturbance/release phase).
- The development of new institutional arrangements to implement the new approaches to water management (i.e. reorganisation phase).

The socio-economic process and the management interventions in the biophysical system can be linked to depict an overall framework for management intervention strategies to achieve sustainability as shown in Figure 6.

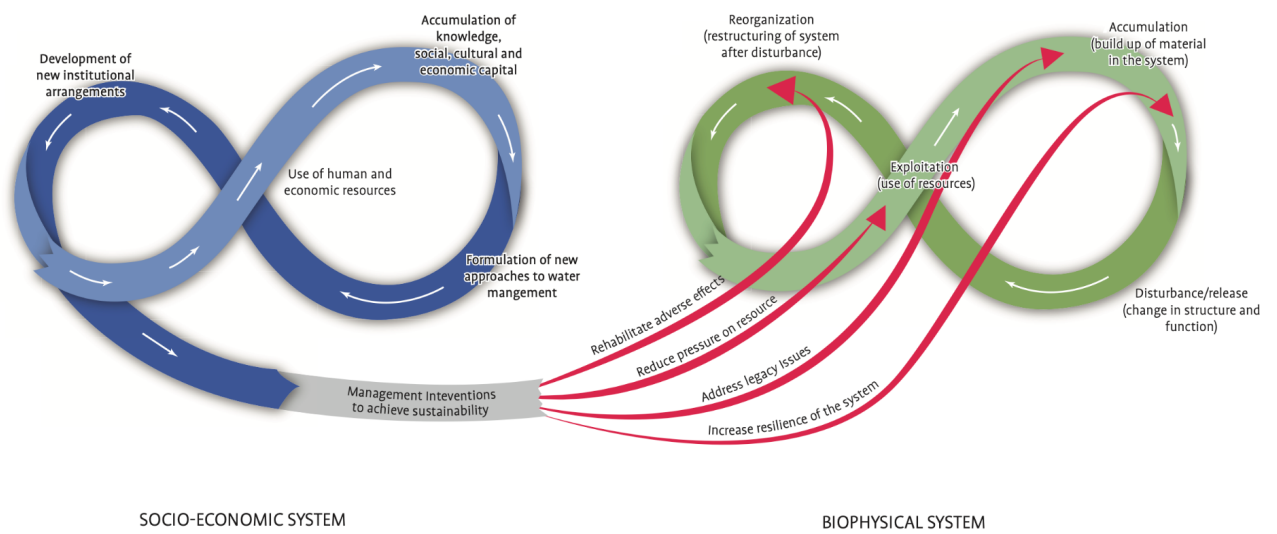
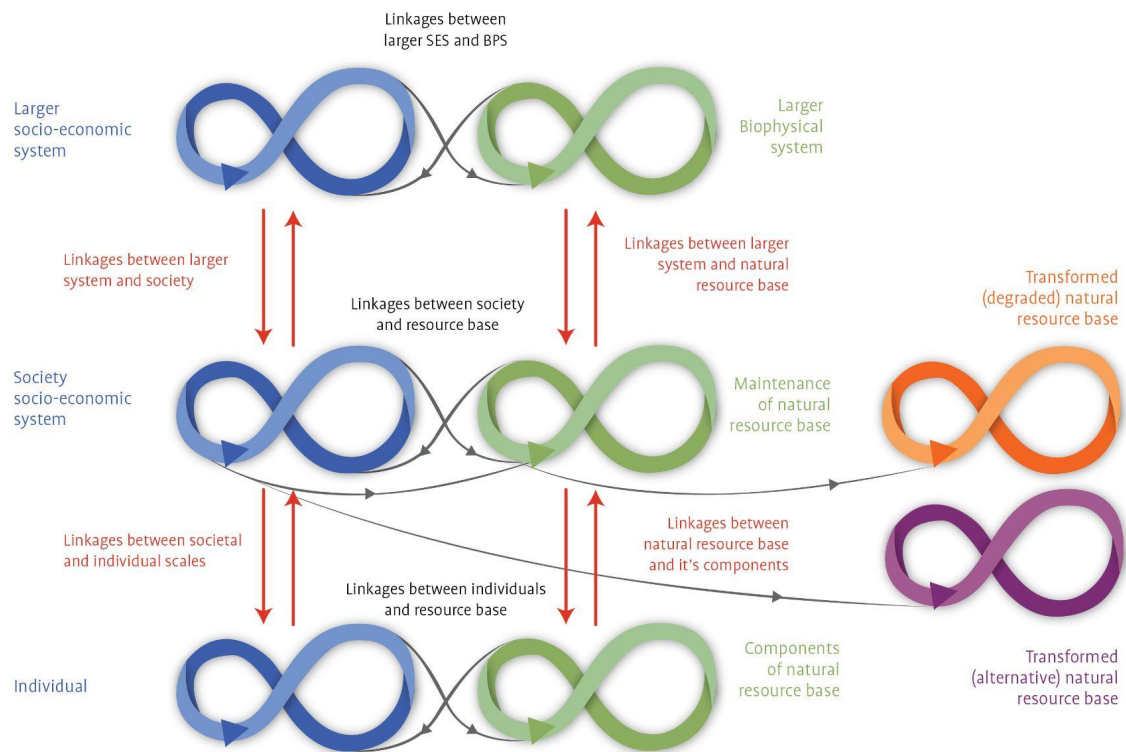


Figure 6 Management Intervention Pathways to Achieve Sustainability [2]

Chapin et al. [6] have provided finer scale approaches which can be classified as components of a nested socio-ecological system. This classification [2] is based on Figure 4 expanded to reflect multiple scales and the links between socio-economic and biophysical systems as well as the links between different spatial scales (Figure 7). The list of sustainability strategies (the seventh key element of the framework) from Chapin et al can be classified into the framework of socio-ecological nested adaptive systems (Table 1).



FRAMEWORK FOR CLASSIFYING APPROACHES TO SUSTAINABILITY

Figure 7 Framework for Classifying Approaches to Sustainability

Table 1 Classification of Sustainability Strategies for a Nested Socio-Economic and Biophysical System

LEVEL	SOCIO-ECONOMIC SYSTEM	LINKAGES BETWEEN SES AND BPS	BIOPHYSICAL SYSTEM	TRANSFORMATION
LARGER SCALE	Adjust governance. Learn from multiple cultural perspectives.	Sustain cultural connections to land and sea. Exercise caution when perturbing larger system.	Sustain slow variables that determine natural capital. Explore system dynamics.	Enhance diversity that provides building blocks for change.
CROSS SCALE LINKAGE TO LARGER SCALE	Stabilise feedback from socio-economic systems.		Stabilise feedback from natural system.	
SOCIETY AND NATURAL RESOURCE BASE	Enhance learning capacity.	Explore consequences of options. Reduce exposure.	Renew functional diversity of degraded systems.	Create new systems.

	Sustain legacies that provide seeds for renewal.			
CROSS SCALE LINKAGE TO SMALLER SCALE	Engage stakeholders.			
SMALLER SCALE		Experiment to test understandings.	Pay attention to vulnerable components.	Foster innovation to create opportunities for change.

Note: (1) It is noteworthy that placing the *list* of Chapin’s strategies into a *tabular* classification of sustainability strategies highlights some gaps in Chapin’s list. In particular, smaller scale strategies in the socio-economic system are not included, such as “farm plans” which are an important part component in nutrient management, and, the linkages between catchment scale and vulnerable components within a catchment such as rivers and lakes.

(2) Gray shading indicates that no entries are possible in these cells.

Connection to Sustainability Transition and Systems Theory

In the context of broader systems theory, the nested adaptive systems approach can be related to Loorbach’s perspectives on sustainability transitions [7] and Cabrera’s concept of DSRP – distinctions, systems, relationships and perspectives [8].

Loorbach describes three prominent approaches to sustainability transition research: socio-ecological, socio-technical and socio-institutional. The socio-ecological approach considers coupled ecological and social systems, and system resilience to disturbance. The nested adaptive systems approach of this paper, particularly the first five elements, follows a socio-ecological approach. The socio-technical approach focuses on dominant technologies that are the subject of transitions. Typical examples are systems in which infrastructure and technologies play an important role, such as energy, transport and water. The socio-technical approach is relevant to the sixth element of the approach in this paper in defining potential management interventions. The socio-institutional approach focuses on the institutional cultures, structures and regimes in which transitional change takes place. Attention is given to the role of agency and governance in transitions. The socio-institutional approach is relevant to the seventh element of the nested adaptive systems approach relating to the process of generating the management interventions and the institutional arrangements for their implementation.

Cabrera’s DSRP provides a view of concepts underlying complex systems. Making *distinctions* involves creating a boundary that differentiates what is in and what is out. Having created a distinction between two entities it is possible to consider the *relationship* between them. A collection of entities and their relationships can be viewed as a *system*. Viewing one conceptual entity from the point-of-view of another comes with a *perspective* or frame of reference [8].

With respect to DSRP, the nested adaptive systems approach makes distinctions between socio-economic and biophysical systems. It also makes distinctions between different spatial and temporal scales. Each distinct component is defined by an adaptive cycle which is dependent on external resources that it can exploit and accumulate material and energy to maintain the system component. Each system component is

also subject to external disturbances that can threaten the sustainability of the system component. Reorganisation after disturbance can lead to recovery (sustainability) or shift to an alternative system.

Further, the system components are connected as part of a larger complex adaptive system. There are linkages between the socio-economic and biophysical systems as well as linkages between the different spatial and temporal scales. A key to understanding the functioning of nested adaptive systems is the relationship between the phases of the adaptive cycle, the relationships between the different spatial and temporal scales, and, the relationship between the socio-economic and the biophysical systems.

Understanding these relationships facilitates the development of management interventions for achieving sustainability strategies. A key aspect of the development of sustainability strategies is taking the perspective of the sustainability of the biophysical system. This involves developing the processes in the socio-economic system to define management interventions to achieve a sustainable biophysical system.

Application of the Systems Framework to the Canterbury Water Management Strategy

Water Management Issues in Canterbury

The Canterbury region (45,346 km²) is on the east coast of New Zealand's South Island and in the rain shadow of the Southern Alps (Figure 8). Nearly 90% of the consumptive water use in Canterbury is for irrigation. With the expansion of dairying the demand for irrigated land has increased from an estimated 100,000 ha in 1982 [9] to 507,000 ha in 2015 [10].



Figure 8 Canterbury Region

Irrigation expansion resulted in cumulative effects of water extraction reaching sustainability limits of water availability as well as land use intensification from irrigated farms compromising water quality and freshwater ecosystems. There was intense conflict between those seeking more water for economic growth and those concerned with ecosystems, and, fishing and whitewater recreation.

Analysis of future water requirements indicated weekly demand for run-of-river irrigation schemes could not be met from available river flows. Annual demand could be met but required storage. An initial strategic study proposed storages on Canterbury's alpine rivers to meet future water demand ([11], and led to further technical investigations to identify storage sites [12]. This raised further community concerns in relation to the effects of storages on braided alpine rivers.

The legislative processes under the Resource Management Act were "effects-based", allowing resource use while managing environmental effects of proposed development within environmental limits. The action-forcing mechanisms were defining rules for development through regional plans, setting conditions through project-specific resource consents, and monitoring compliance with rules and conditions.

There is an Environment Court to hear appeals and has the power to review the technical merit of decisions making resource management highly legalistic and with an adversarial style of decision making. Court interpretations have defined an "overall broad judgement" approach to resolving conflicts between resource use and environmental protection [13]. The overall broad judgement approach has allowed Environment Court judges and commissioners hearing development applications to approve further development despite limitations on water availability or degraded water quality.

It was recognised that there was a need for a paradigm shift in water management.

Canterbury Water Management Strategy

Following the success of collaborative approaches at the tributary and catchment scales for resolving water management issues, a regional strategy was developed [14] based on Ostrom's principles for governing common pool resources [15], and Gunderson and Holling's approach of nested adaptive systems [3].

The Canterbury Water Management Strategy (CWMS) was developed based on issues at four spatial scales [16]:

- the regional level, where the key issues are water availability and land use intensification;
- the catchment level, at which the sustainability levels of water use and its effects, cumulative impacts of water use, and the reliability of supply are the main issues;
- the subcatchment level, where environmental flow requirements in river reaches, and management of streams and their riparian margins are the most significant issues; and
- the property level, where the land use practices that influence water quantity and quality are defined.

The CWMS was facilitated by the regional council and led by a multi-stakeholder group with oversight by the Canterbury Mayoral Forum. Extensive stakeholder and community engagement was undertaken on water uses and strategy options [17]. Strategic investigations informed both the strategy selection process and a sustainability appraisal based on environmental, economic, social and cultural criteria [18]. Using stakeholder input, the CWMS established targets for ten community water uses not just water availability. The CWMS demonstrated that improved water use efficiency of existing users was a more cost-effective and sustainable way of improving water availability compared to storage. Dams on the mainstems of alpine rivers were precluded, and alternative forms of storage were identified (e.g. off-river storage, managed aquifer recharge, on-farm storage) to improve supply reliability for irrigators. Improved water use efficiency and land management practices at the property scale were identified. New nested governance arrangements were established with ten multi-stakeholder Zone Committees established to generate Zone Implementation Programmes for catchment-level issues, and a Regional Committee to develop a Regional Implementation Programme for regional issues, such as regional water infrastructure. For operational management, farmer collectives based on tributary catchments and irrigation districts are being established to develop Environmental Management Systems (EMS) to achieve water management objectives, and farmers prepare Farm Environmental Plans consistent with the EMS which are independently audited.

Water Strategy as a Nested Socio-Economic and Biophysical System

The CWMS evolved from the initial concerns of earlier strategic studies about water availability and the perceived need for major storages on alpine rivers. Table 2 sets out the components of the original storage “solution” in the framework for classifying approaches to sustainability. The regional transformation based on “Storage on alpine rivers” is added to “Run-of-river supply” within “Allocation limits” at the

catchment level, “Environmental flow for river reaches” at the subcatchment level, and, “Consents” at the property level.

Table 2 Components of a Storage Approach to Water Availability in Canterbury

LEVEL	SOCIO-ECO NOMIC	LINKAGES SES AND BPS	BIOPHYSICAL SYSTEM	TRANSFORM ATION
Canterbury Region				Storage on alpine rivers.
Linkage to region				
Catchment		Allocation limits.	Run-of-river supply.	
Linkage to subcatchment				
Subcatchment			Environmental flow for river reaches.	
Linkage to individual				
Individual	Consent			

Note: Gray shading indicates that no entries are possible in these cells.

The CWMS is more comprehensive. Table 3 sets out the water availability components of the CWMS in the framework for classifying approaches to sustainability. The CWMS includes a wider range of components, for example, the addition of water use efficiency measures, and monitoring for management. Storage on mainstems of alpine rivers is excluded because of concerns about the impacts on braided rivers, but a wider range of storage options is included, for example, on-farm storage, irrigation scheme storage, groundwater storage, and storage associated with alpine rivers such as off-river storages and diversions to tributary storage. Significantly, the CWMS includes socio-economic components, for example, regional committees and zone committees to develop implementation programmes [19].

Table 3 Key Components of a Sustainability Strategy for Water Availability in Canterbury

LEVEL	SOCIO-ECON OMIC SYSTEM	LINKAGES SES AND BPS	BIOPHYSICAL SYSTEM	TRANSFORMATION
Canterbury Region	Regional Committee.	Integrated water management.	Regional infrastructure.	Storage associated with alpine rivers.

Linkage to region	Regional Implementation Programme.		Inter-basin transfers.	
Catchment	Zone Committee; Moratorium on consents.	Allocation limits; Reallocation of consents.	Run-of-river supply.	Groundwater storage.
Linkage to subcatchment	Zone Implementation Programme.		Piped distribution.	
Subcatchment	Farmer Collectives.	Real time monitoring of total take.	Environmental flow for river reaches.	Irrigation scheme storage.
Linkage to individual	Environmental Management System.		Real-time monitoring of take.	
Individual	Farm Environmental Plans.	Audited monitoring.	On-farm irrigation efficiency.	On-farm storage; Improved land and water management.

Note: Gray shading indicates that no entries are possible in these cells.

Managing Based on Nested Adaptive Systems

The primary means of managing natural resources within sustainability limits is to define limits for environmental parameters and manage impacts to be within these limits. New Zealand has established a National Objectives Framework which defines water quality attribute states for setting limits [20].

Problems Experienced with Managing to Limits

However current experience with implementing the “managing to limits” concept is showing some significant challenges in relation to this concept achieving sustainable outcomes. These challenges include: (a) uncertainty of the numerical value of the limit; (b) inaccuracies and differences in models used for limit estimation; (c) natural variability in the parameter used to define the limit; (d) multiple variables influencing the parameter used to define the limit; (e) enforceability of limits which lack clarity and certainty; (f) contributions from legacy issues as well as current activities; (g) lag time between the activity being managed and the effect in the environment; (h) ascertaining the cause of changes when monitoring for the limit; and, (i) the range of management interventions to address exceedances of the limit [2].

These challenges are considered below in the context of the current work in Canterbury to introduce nutrient load limits to manage eutrophication and algal blooms. The result of considering these challenges is that while managing limits is valuable in identifying critical variables with respect to resilience thresholds, it is not enough to achieve sustainable outcomes. Rather there needs to be a transition from a regulatory approach of managing to bottom lines to a collaborative approach of the delivery of sustainable outcomes based on nested adaptive cycles.

In the study of options for nutrient load limits in the Hurunui catchment, Norton and Kelly [21] noted three sources of uncertainty: measurement error, incomplete data and models, and natural variability. Estimates of the current mean annual nutrient loads showed a range of values, e.g. the mean annual Dissolved Inorganic Nitrogen (DIN) load for the Hurunui River at State Highway 1 (SH1) was stated as 654-731 tN/y to reflect the estimated uncertainty.

Brown [22] in his evidence to the consent hearing for Ngāi Tahu irrigation proposal for the Balmoral Forest identified four different valid methods for calculating the annual DIN load at SH1 (averaged over 5 years). The methods showed a range from 732 to 818 tN/y and Brown concluded that there was no perfect method.

In relation to natural variability for the Hurunui nitrogen loadings, Brown calculated the annual DIN load at State Highway 1 for the seven-year period from 2005/6 to 2012/13. This showed an annual variation from 445 tN/y to 981 tN/y. Not only was there substantial variation in nitrogen loading from year-to-year, but also the greatest periphyton cover (49 days in excess of 20% cover) was in the year 2005/6 when the annual load was only 521 tN/y [23]. Figure 9 shows the practical difficulty of managing to a limit. If the objective is maintaining the current annual average level (i.e. 693 tN/y) then the left-hand graph shows the intended concept of values below 693 tN/y being considered “acceptable” and values above 693 tN/y being “unacceptable”. The right-hand graph shows the actual situation of year-to-year variations and an allowance for uncertainty. This indicates that there is uncertainty about whether the annual load is above or below the limit for results between 420 tN/y and 1019 tN/y.

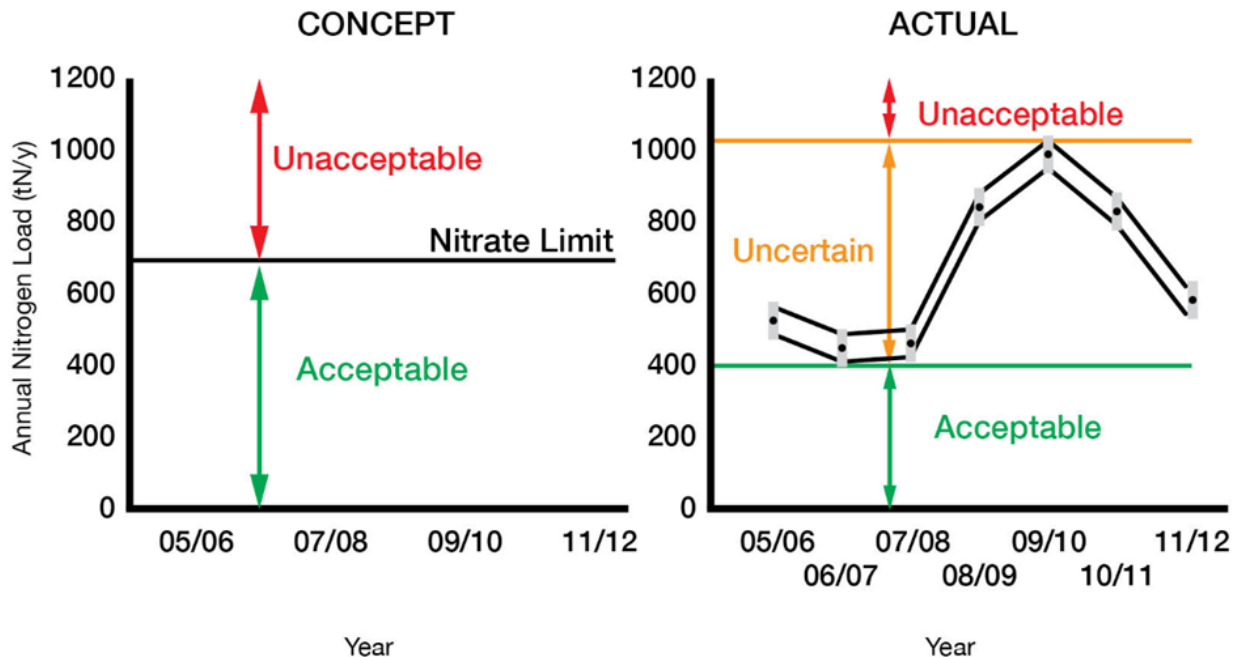


Figure 9 Managing to Limits allowing for Natural Variability and Uncertainty [2]

It is not just natural variability. There can be multiple variables involved in determining the sustainable outcome sought of managing periphyton cover to acceptable levels. The maximum abundance of periphyton is not only related to the nutrient loads and concentrations. It is also related to the time available for biomass to accrue between flushing flows that dislodge periphyton from the streambed, to temperature, and, to the amount of light available [24].

In developing the National Objectives Framework (NOF) for periphyton, consideration was given to natural variability by incorporating two factors in setting the objectives: one was the time period between freshes that can remove periphyton, and the other was the degree of natural nutrient-enrichment associated with the geology of the catchment. The periphyton objective is defined in terms of an abundance threshold measured as chlorophyll *a* (200 mg/m²), and a maximum exceedance frequency. In general, the objective is for exceeding the threshold for no more than 8% of samples taken monthly over a three-year period. For dry climates (i.e. with longer periods between freshes) and for naturally nutrient-enriched catchments (i.e. catchments with soft sedimentary geology or volcanic soils) threshold exceedance is allowed for 17% of samples [24]. However, while this approach accommodates natural variability, threshold limit values can only be assessed after three years of data. This represents a poor basis for a trigger mechanism for management intervention or regulatory action. Limits are only enforceable when they are timely, clear and certain.

Another influence on setting contaminant loads is discussed by Norton [25] in his report for the proposed Hurunui and Waiau Regional Plan: the volume of streamflow is important in the dilution of nutrient loads. As extraction of water from the river increases, the volume available for dilution decreases; this means that the instream concentrations of nutrients increase. Thus, the nutrient load that the environment can accommodate while still achieving the defined in-river outcome decreases with increasing allocation for extraction.

Because of natural variability and multiple sources there are advantages in having independent means of identifying the likely sources of any increases in contaminant levels. Brown [22] highlights for the Hurunui catchment the need to monitor nutrient loss rates from farms, tributary loads and mainstem loads to identify likely sources of any increases. This means that in order to identify whether management and/or enforcement intervention is warranted, managing contaminant load limits is not sufficient. While managing a specific load limit can be a useful component, it is also necessary to examine the overall system to develop management interventions to achieve sustainability. There is value in considering the adaptive cycles for nutrients as a basis for establishing appropriate management interventions. As an example of this approach the management of algal blooms in rivers is set out below.

Adaptive Cycles as the Basis for Management

For periphyton in rivers, there are a suite of management interventions to achieve the delivery of sustainable outcomes at the catchment scale and the streambed scale. Table 4 sets out the adaptive cycle phases for the catchment scale and the streambed scale for periphyton in rivers (as shown in Figure 3 above). The table indicates the critical variables and provides examples of management interventions for each phase. This includes managing to limits: firstly, nutrient loss rates relate to the catchment exploitation phase (nutrient intensive farming) with improved farm management practices to reduce loss rates as an example of a management intervention; secondly, catchment contaminant loads relate to catchment accumulation phase of the cumulative effect of diffuse and other nutrient sources with the specification of catchment nutrient limits as a management intervention; and thirdly, instream nutrient concentrations relate to the streambed exploitation phase with nutrient concentration limits as a management intervention.

Table 4 Adaptive Cycle Phases and Management Interventions for Periphyton in Rivers

ADAPTIVE CYCLE PHASE	CRITICAL VARIABLE	EXAMPLE OF MANAGEMENT INTERVENTION
Catchment Exploitation: nutrient intensive farming	Nutrient loss rates	Improved farm management practices to reduce loss rates
Catchment Accumulation: cumulative load of nutrient sources	Catchment contaminant load	Catchment limit on contaminant load
Catchment Disturbance: contamination of runoff and groundwater	Nutrient concentration in surface runoff and groundwater seepage	Riparian planting; Woodchip bioreactors
Catchment Reorganisation: nutrient attenuation	Nutrient attenuation factors	Constructed wetlands
Streambed Exploitation: nutrient contamination of river	Nutrient concentrations, temperature, light	Concentration limits for nutrients; Shading of streambed
Streambed Accumulation: build-up of periphyton	Accrual period between flushing flows	Maintenance of freshes in environmental flow requirements

Streambed Disturbance: potential for algal blooms	Periphyton cover; Chlorophyll <i>a</i> level	Public health warnings
Streambed Reorganisation: recovery from algal blooms	Flushing flows; Invertebrate grazing	Sediment removal to increase invertebrate habitat

The use of the nested adaptive systems framework illustrates other avenues for management intervention. At the catchment disturbance phase (contamination of surface runoff and groundwater seepage) other interventions include riparian planting for surface runoff and woodchip bioreactors for groundwater to reduce nutrient concentrations in runoff and groundwater respectively. At the catchment reorganisation phase of nutrient attenuation, constructed wetlands are a possible management intervention to increase the critical variable of catchment attenuation factor.

At the streambed scale exploitation phase, in addition to nutrient concentration limits, light and temperature management through vegetation shading is also a potential management intervention. The accrual period (the time between flushing flows) is a critical variable for the streambed accumulation phase of periphyton build-up; this can be managed by environmental flow requirements to maintain flushing flows. The streambed disturbance phase is the occurrence of algal blooms with chlorophyll *a* levels or periphyton cover as the critical variables. Public health warnings are one form of management intervention. The final phase of streambed reorganisation (the recovery from algal blooms) depends primarily on flushing flows and invertebrate grazing to reduce algal biomass. Management interventions include sediment removal to improve invertebrate habitat. Without adequate interventions, algal biomass will continue to grow leading to ongoing stream degradation.

Conclusions

The systems approach based on nested adaptive cycles and collaborative governance has led to a paradigm shift in water management in Canterbury. The traditional approach of effects-based management and adversarial legal processes led to sustainability limits being reached and unresolved community conflict. There is now a governance approach at different spatial scales to facilitate sustainable development and community agreement on the multiple community objectives for water. Furthermore, there are indications that operational management based on managing to limits is not enough to achieve sustainable management. Rather, management based on nested adaptive cycles and collaborative governance is needed.

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