Conceptual framework for catchment-scale integrated water resource management

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Abstract

This paper presents an integrative conceptual framework designed to enable interdisciplinary understanding of the dynamic linkages between the ecological, social and economic components of human-environment systems associated with water resource management, over time. It is underpinned by interdisciplinary theory concerning the ways in which environments affect people by constraining or enabling various forms of behaviour, and people affect environments through their actions, at various scales. The framework can be used purely conceptually, identifying the nature of a catchment system and linking the work of team members from different disciplines, or numerical and spatial data can be attached to the conceptual framing . By focusing on cause-effect relationships throughout the complex system constituted by any catchment, the framework can then be used to focus on specific management issues within their contexts.

The framework is built up in four stages, considering the water cycle, the catchment in spatial and temporal terms, systems analyses of people-environment relationships, then applications. The basic framework can be populated with combinations of qualitative and quantitative data, and the systems analyses can be elaborated using conceptual and mathematical models including causal loop modelling, systems dynamics modelling, or Bayesian belief networks. The spatial ‘stage’ is designed to be visualised, like a map: this can be built up in layers, as in a geographic information system (GIS), selecting the subsystems and related information layers deemed important to address an issue or research problem. Thus the framework enables research teams to nest systems-based conceptual frameworks relevant to the issues they need to explore - such as broad linkages between water availability and human habitation or between culture and land use - within a mapped conceptualisation of a catchment.

The precise nature of the systems linkages needs to be explored for the specific country, location and issues of the study. The framework is intended for use in a variety of societies reflecting differing cultures and where quantitative scientific data may be scarce. The framework is generic and can also be applied to regions where water resources need not be the main focus. Our paper canvasses the way in which the framework is tailored for water resource issues.

INTRODUCTION

The understanding required to manage water resource issues successfully is inherently interdisciplinary, involving biophysical, social and economic factors, frequently applied through engineering, governance and budgetary processes. In both science and management, we need a clear idea of how people and their activities affect water resources (in conjunction with the many natural elements affecting the water cycle) and how water resource issues affect people. Our collective experience working in many interdisciplinary teams is that interdisciplinary teams need a common frame of reference. Members of newly formed teams, particularly if they have not worked on interdisciplinary projects before, often struggle with concepts, and terminology. In other words, the first challenge for an interdisciplinary team is with the intellectual and practical ‘framing’ of issues: what is important, what is linked to what? Initially individuals may jockey to assert their specific framings, rather than work to see the part their conceptual understandings and expertise play in a greater whole. Our experience is also that different team members are comfortable working at different scales and levels of detail. A flexible and accessible common framework should allow them to ‘nest’ their preferred scale among others.

The conceptual framework presented here, a work in progress, is intended for use by interdisciplinary research and management teams involved in water resource management. It arises from the needs of the International WaterCentre (IWC) as an interdisciplinary, inter-institutional[1] and internationally-focused research-to-management body needing a common framework to underpin its understandings and research. Leadership in developing this framework comes from one of IWC’s current projects, the Australian Water Resource Facility project – supported by the Australian Agency for International Development (AusAID) – which will conduct interdisciplinary, ‘whole of water cycle’ research to contribute to AusAID’s development cooperation program in the water sector, with a focus on risk assessment and the development of indicators.

CATCHMENT FRAMEWORK

Conceptual frameworks come in various forms, with varying degrees of linkage to theory (Ross and McGee 2006, Robson 2002). They may be visual, rendered as a mind map or flow diagram, or in text, for instance as dot points or principles. Depending on their purpose, conceptual frameworks may be compiled from a combination of literature, discussion, “expert”[2] opinion and available data. Common techniques include mind mapping of key elements and linkages (thus capturing the implicit theories of the team), or more formal systems analysis.

The following framework is just that – designed to ‘frame’ discussion or an investigation. It is a housing for concepts and systems understandings, taken at a whole-of-landscape scale or considered in more detail at any scale within the landscape. It is also a ‘scoping’ device, helpful to consider what information is needed to study an issue efficiently.

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[1] The International WaterCentre is a consortium of four universities: The University of Queensland, Griffith University, Monash University, and The University of Western Australia. It brings together water related expertise from the four universities, and undertakes joint education and training and applied research. The research team members of both AWRF and IWC come from very different backgrounds. We include biophysical, social scientists and economists, practised in a range of interdisciplinary fields including impact assessment and risk assessment.

[2] “Expert” in this context means anyone with superior knowledge of key processes whether acquired first hand through experience e.g. local farmers or fishermen and government officials, or obtained through formal study and research, such as professional scientists and engineers.

It is important that this framework be used in a selective way to inform each study. It is not necessarily useful to populate every possible aspect and layer of the framework with detailed information, if that will not help to provide either valuable contextual information or specific information needed to enlighten analysis. For instance a study of drinking water systems would need to be detailed with respect to some parts of the catchment system, but could afford to remain sketchy with respect to others, say land uses and natural vegetation. Here it is important to focus on the drinking water system itself, and what currently affects, and is affected by drinking water, *or could be in future*. The aim then is not to document agriculture and irrigation systems for their own sake, but to understand where increasing demand for agricultural water could compete with drinking water needs (or pollute sources), or where other towns' and villages' inadequate sewerage systems could pollute drinking water sources or raise the need for costly treatment.

Unlike many frameworks which can be presented in a single diagram or list of points, the complexity of our issues and the level of understanding we seek has led us to build and focus on the framework as a staged process.

1. The First Stage – Understanding **the water cycle**

The underpinning logic of our framework is that of the water cycle within a catchment context – the whole of water cycle approach). As the first step we describe the natural elements of the water cycle - the "basic" processes, with a focus on hydrological knowledge in a physiographic context, considered initially without linkage to human interventions. This focuses on the main parts of the water cycle, from cloud formation, rainfall, runoff to streams or infiltration to groundwater systems, flows to the ocean, and evaporation/transpiration to reconnect the cycle as cloud formation and further rainfall. These steps interconnect with climate, topography, soils and vegetation, which affect how much rain falls and where, how much runs off, is stored as soil moisture or becomes ground water, how much is taken up by vegetation or evaporates from streams. By starting this way with processes that are often familiar to all participants a backbone of information and understanding is established within the team that also provides the basic knowledge architecture to the framework.

As a second step the team then considers human and environmental needs and uses 'attached' to each part of the water cycle within the framework (see figure 1). Human usage and restructuring activities amend this basic cycle in many ways. Uses include drinking, irrigating crops, uses in manufacturing and leisure, landscaping and aesthetic enjoyment. These uses are mediated by supply systems, which involve both infrastructure and institutional arrangements. Supply systems generally involve modifications to the water cycle including channelling, damming and piped water distribution systems, water treatment and waste disposal systems. We will return to these shortly.

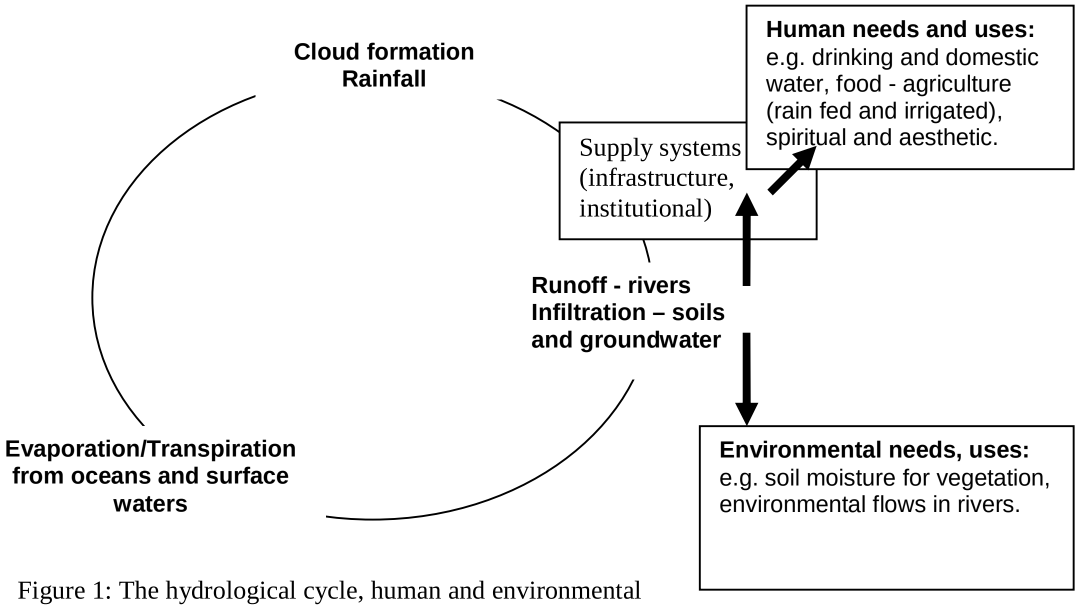

Figure 1: The hydrological cycle, human and environmental needs and uses

The third step within this stage is to consider the institutional arrangements associated with these uses of water, whether these be customary or formalised in national institutions. Customary institutional arrangements include cultural taboos on contamination of water sources (often associated with spiritual values associated with water or protecting forests), and common property arrangements for sharing of irrigation water. Formalised arrangements include all parts of systems of governance for water as well as overarching governance systems which affect water resources. These typically include legislation and regulations, organisations, decision-making processes including consultation processes, and financing arrangements. Thus our framework focuses both on the tangible uses of water, and the less tangible arrangements that govern – or attempt to govern - that use.

2. Stage 2 - Catchment-based schematics

The next conceptual step is to consider how the elements of the water cycle, and the human and environmental needs and uses of the cycle, are distributed or interact across space and time. Our framework has strong spatial foundations, for three reasons. First, members of interdisciplinary teams are likely to be able to relate to spatial rendering, since most of us (in most, but not necessarily all, cultures) recognise landscapes. Second, a spatial rendering enables thinking and work at multiple scales: one simply needs to think in terms of zoom lenses, zooming in to finer scales and zooming out to broader scales. Third, a geographical scale enables frameworks to integrate with GIS as data and models are added. A temporal understanding is also necessary, to understand daily, seasonal and year-to-year fluctuations in weather and climate, water availability and use. A historical view of the development of water resources can also be useful.

Our schema of a catchment – or subcatchment, or set of catchments forming a region - may include, according to the needs of each study, the natural system and human modifications including settlements and engineered systems of water supply and waste disposal, land uses and landscape modifications. At this stage it may be appropriate to map some ‘institutional’ aspects, including land tenures (protected areas, private property), though these are discussed at a later stage (see below).

The classification of systems outlined below takes a ‘needs’ focus, considering environmental needs for water (such as environmental flows for ecosystem health), and human needs for water.

‘Natural’ system

Relevant spatial features of the natural system include

- the surface water body network, including rivers and streams, lakes and wetlands, estuaries and coasts
- aquifers and ground water
- topography (in GIS terms, a Digital Elevation Model), soils, vegetation cover and types, and other landscape components known to affect or be affected by the water cycle
- climate and weather, including seasonal and inter-seasonal weather patterns.

The team may add other ‘natural’ layers of interest according to the issues of study, for instance species distributions such as birds and fish, in their natural vegetation and water habitats.

Temporal variability is important also. Questions arise such as: are there seasonal and inter-seasonal variations in flow regimes, or are there relevant long-term trends, including the projected impacts of climate change?[3] Mapping of critical process time scales needs to include cycles relating to human use (to which we turn below). Is irrigation use greater at some times of the year than others? Is it tied to crop rotation? When does water scarcity occur and why? By asking these types of questions and mapping them in a conceptual way once the basic schema has been built, underlying assumptions and key paradigms driving these assumptions within the different disciplines are frequently brought to light. As a result they are made explicit as important parts of the framework, and in the process other team members are obliged to consider them in the light of their own understanding and accommodate them accordingly.

At this stage the interest is on the main conceptual elements representing the ‘state’ of the system, providing the context for considering pressures and responses. These will become important as teams add systems analyses to their customised versions of the framework (see below).

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[3] Discussion of temporal issues may initially lead to confusion within a research team. Experience has shown that it is important that the first round of schema building is done using an agreed time frame appropriate to the spatial scale of interest e.g. annual processes if working at a catchment level. Subsequent schema can then be built to identify or isolate critical time dependant processes such as seasonal differences.

The human-modified system

Stage 1 and Figure 1 illustrated that human needs for water, and products (such as food) dependent on water, are mediated through supply systems, which are both institutional and engineered. Institutional arrangements include customary or legislated systems of water entitlements, water sharing arrangements, financing (or other resourcing such as inkind labour inputs within customary systems), maintenance arrangements, and sanctions for misuse. 'Engineered' elements include the distribution system (pipes, channels), treatment plants and waste disposal systems governed by and produced under the existing institutional arrangements.

The human-modified system could be classified for framework-building purposes in various ways. After considering alternatives, we have settled on a needs-based conceptualisation following the classification of human needs of Maslow (1954). Maslow argues that all individuals and societies need to meet five key needs, with the higher order needs becoming more relevant as the basic needs are satisfied (and less relevant when the most basic needs are under threat). These basic needs are survival (food and shelter), social needs (love and the esteem of others) self-esteem, and once these are satisfied, self-actualisation (self-fulfilment). Dependence on the biophysical environment - whether natural, cultivated or constructed - is thus fundamental to many human needs, particularly the survival needs. It is less directly associated with the social needs (though water-based recreation can be a social activity) , but for some people is quite strongly identified with the highest need of all, personal fulfilment. Our adaptation focuses on recreational uses of and spiritual attachments to water and its associated environments at this level of the hierarchy of needs. This needs-based classification also represents consumptive and non-consumptive uses of water, with the non-consumptive uses shown as higher order needs.

Thus water, and assets produced using water, can be considered in terms of its contributions to survival needs, but also to social and self-fulfilment needs including spiritual dimensions.

These needs are summarised in table 1.

Table 1: classification of needs for water

Nature of need		**Considerations**
Environmental needs for water	Environmental needs for water e.g. environmental flows.	Dependency of important ecosystems on an appropriate quantity or quality of water. Biodiversity in aquatic ecosystems, and in terrestrial ecosystems where suitable water quantity and quality may be at risk.
	Ecosystem services affecting water quantity and quality, or affected by these.	The linkages between natural assets that combine to produce ecosystem services.
Human needs: Water towards survival needs (consumptive uses)	Drinking and domestic water cycles.	Where is water taken from, any distribution infrastructure, treatment system and location if any, where and how is it used and in what quantities (overall and per person), where and

		how is waste-water disposed, and with what levels and types of treatment. (It is possible to attach quantities, such as volumes available, distances of pipe, treatment capacities or water quality figures, where known, at each stage). The institutional arrangements and any other social and economic factors governing or influencing how drinking and domestic water is allocated and delivered. Here it is important to consider both customary and legislated systems.
	Food production and consumption cycles: How water is used directly and indirectly in the production, then consumption, of food.	• Rain fed agriculture (adequacy of quantities and distribution of rainfall, hydrological capacity for expansion or intensification of cropping, including movement to irrigation, run off, water retention in soils and streams, any contamination issues in run off). • Irrigated agriculture – from surface water and from ground water. (Nature of infrastructure systems e.g. dams and channels, bores; institutional arrangements in their development and maintenance including customary management, other administrative systems; financing of the system including any subsidies] • Stock watering systems (direct from streams, or through piped systems and watering points) and effluent effects (e.g. stock contamination of rivers). • Other roles of water in agricultural production e.g. uses of water in dairy cleaning. • Uses of water in agribusiness e.g. water as input to processed foods, water usage for cleaning in agricultural industries (factories). • Factors associated with unprocessed or processed food consumption (e.g. contaminated foods through inadequate cleaning). • The economic arrangements influencing the availability of water towards production of food (e.g. market factors) • The institutional arrangements influencing the availability of water towards production of food (e.g. property rights in water, water law and customary systems, governance arrangements, water sharing, water trading systems).
	Water as part of housing and urban systems (see also drinking water above)	o Supply system to settlement and house o Treatment and disposal systems to settlement and house

		o Water in the urban landscape. Wanted e.g. natural and artificial water features in landscaping, such as water courses and lakes. Unwanted e.g. drainage of rain runoff (free flowing or piped?), o Water roles in industry (see for agribusiness above, and extend to manufacturing). Water may have input roles e.g. water in ice cream production, commercial cooking; cleansing roles, o System for waste disposal, treatment of wastes, and fate of wastes (in the absence of systems) for all of the above. o The economic arrangements influencing the availability of urban water (e.g. financing and user-pays systems) o The institutional arrangements influencing the availability of urban water (e.g. customary rules, governance arrangements, legislation).
Water in social and self-actualisation needs (non-consumptive uses)	Water resources in recreation	o Visual attraction (water – river, lake or coastal – these make a high contribution to scenic amenity in landscapes) o Secondary visual attraction e.g. bird and animal watching where water bodies provide habitat o Primary and secondary contact eg. Swimming, water sports o Attraction of settlement, e.g. tourism infrastructure such as hotels, golf courses to water-scenic environments.
	Water in spiritual fulfilment and self-actualisation	o Meaning of water, and specific water bodies, to various cultures and to local residents (e.g. sacredness of pools and rivers) o Calming effect of water (see recreation and urban landscaping)

For all of these systems, we ultimately need to know about

- *Flows* of water through all of these, e.g. flow rates in streams, quantities of water discharged (quantity issues), temporality in these flows.
- *Quality*, e.g. water quality at different points in the system.

Maslow’s concept of a hierarchy of needs reminds us that higher order needs tend to prevail only where survival needs are met – communities and individuals struggling for survival are often ready to forego water for recreation and perhaps even for spiritual needs, though there may well be competition between the well off and the poor with respect to water priorities. Note that some of the human uses for water listed in table 1 relate also to environmental needs.

In later sections we will elaborate how each of the needs for water, and their related systems and issues can be considered within systems analyses, and how the framework can be used towards risk assessment (see stage 3 below).

Figure 2 illustrates the ways in which needs and uses for water attach to various parts of the water cycle, linking stages 1 and 2.

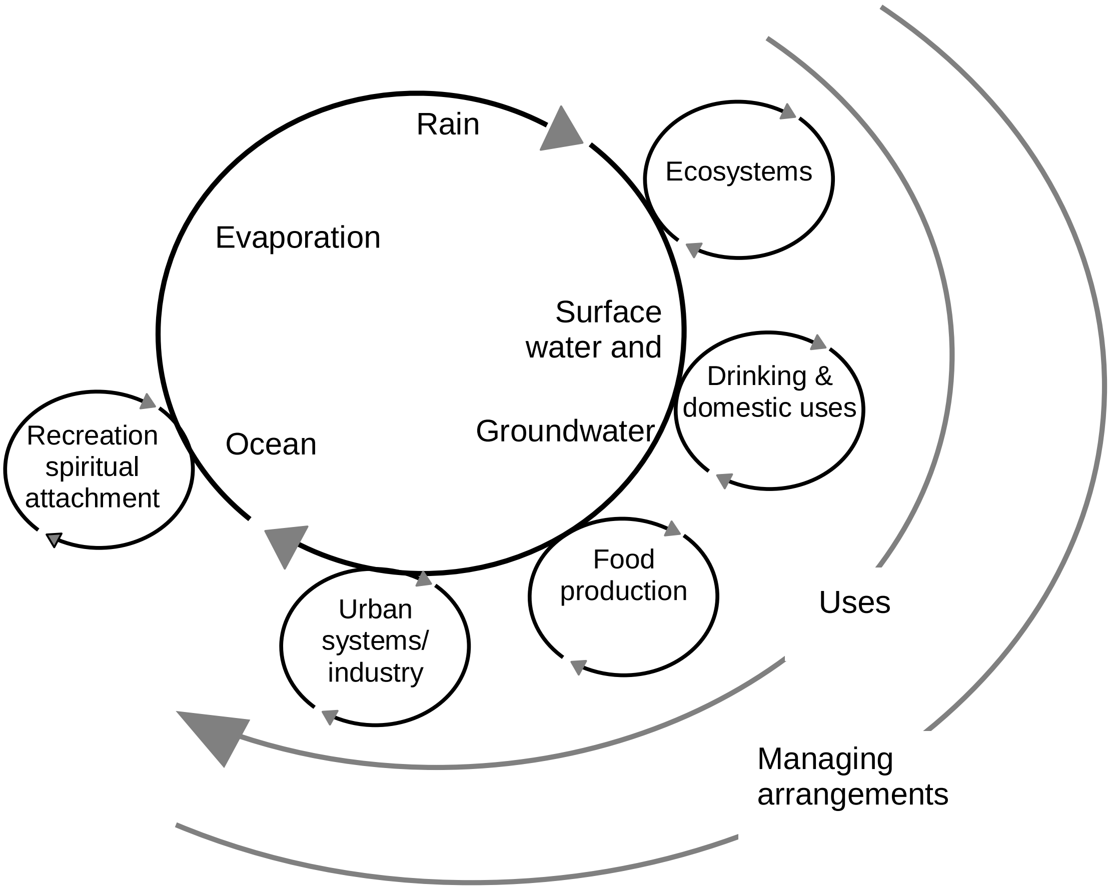

Figure 2: Whole of water cycle

The linkages illustrated in figure 2 need to be considered in a spatial way, for instance where are ecosystems perhaps stressed for lack of water or at risk of losing water; where are drinking water supplies drawn from and how are they delivered to households; where and how does food production use ground water, rainfall, or irrigation from surface waters; and which water bodies are important for recreational purposes or have spiritual significance to local people?

The spatial aspect of the framework is also important to identify diversity within catchment systems. Any of these systems are likely to play out differently in different spaces, for instance the supply of drinking water to a village and to a city, even within the same catchment, could well differ in terms of the source of water, the quantities and quality of the source water, delivery infrastructure including any treatment, social norms governing usage and avoidance of contamination, institutional arrangements, and financing. In essence, there may be different systems for meeting the same type of need (drinking water), or they may operate somewhat differently (for instance where water is abundant versus where it is scarce).

We mentioned earlier the idea that users can ‘zoom lens’ within this conceptual framework. We envisage this happening in two ways:

- spatial ‘zoom lens’, in for a closer look at areas, or out for a broader (and perhaps comparative) view
- temporal ‘zoom lens’, selecting time periods for consideration
- thematic ‘zoom lens’, extracting one system, such as drinking water supply, or irrigation water; or one issue, such as water quality, for closer examination.

In each case, ‘zooming’ assists conceptual clarity, while the retention of the broader framework reminds users to remain aware of related systems and subsystems within the area (alternate and potentially competing uses for water within the same area or those connected hydrologically). The awareness we seek is that of ‘nested’ systems, each available for separate consideration but related to others at neighbouring scales, and in alternate uses of water.

3. Stage 3 – Refining Systems analyses

The catchment-based schematics can now be considered in terms of what affects, and is affected by the water cycle, and environmental needs for water – in line with a human classification we adopted above. Systemic connections include the relationships between climate, topography, soils and vegetation (affecting rainfall, streamflow and infiltration), and in turn the ways in which soil (erosion), vegetation and the presence of species is affected by the availability of water. A useful way of thinking about this is in terms of influences (Abel et al. 1998): what influences streamflow (or other part of the water cycle); what is influenced by streamflow?

The spatial schema described above, focused on crucial aspects of the water cycle, provides a basis for the analytical part of the framework. While we have mentioned systems of water usage above, related to human and environmental needs, the conceptualisation so far remains somewhat static: it needs to recognise human interventions in the water cycle, and their consequences for both environment and society, in a holistic, systemic way. For instance, depending on the research issues, we probably need to know about human activity patterns and their extent and ways of using water, and we may well need to consider trends such as population growth or climate change and their implications. This brings us to the task of conducting systems and sub-systems analyses in relation to the issues. The spatial basis of the framework encourages us to consider the variations that may be necessary in these systems analyses in different parts of our catchment, or at least variations in the data inserted.

Teams may choose which tools they prefer to explore and delineate systems and subsystems of interest. Simple mind mapping, and 'soft systems analysis' (Checkland 1980, Checkland and Scholes 1990) can be useful to set out the main influences between natural and human elements in a system, identifying critical interactions and feedback loops. Bayesian networks analysis, or systems dynamics, can also be used to elicit the main connections, while providing capacity to explore the connections in more detail and to link to data or mathematical models. Here we illustrate the use of 'causal loop modelling', recognising that not all systems necessarily 'loop' neatly.

Causal loop models

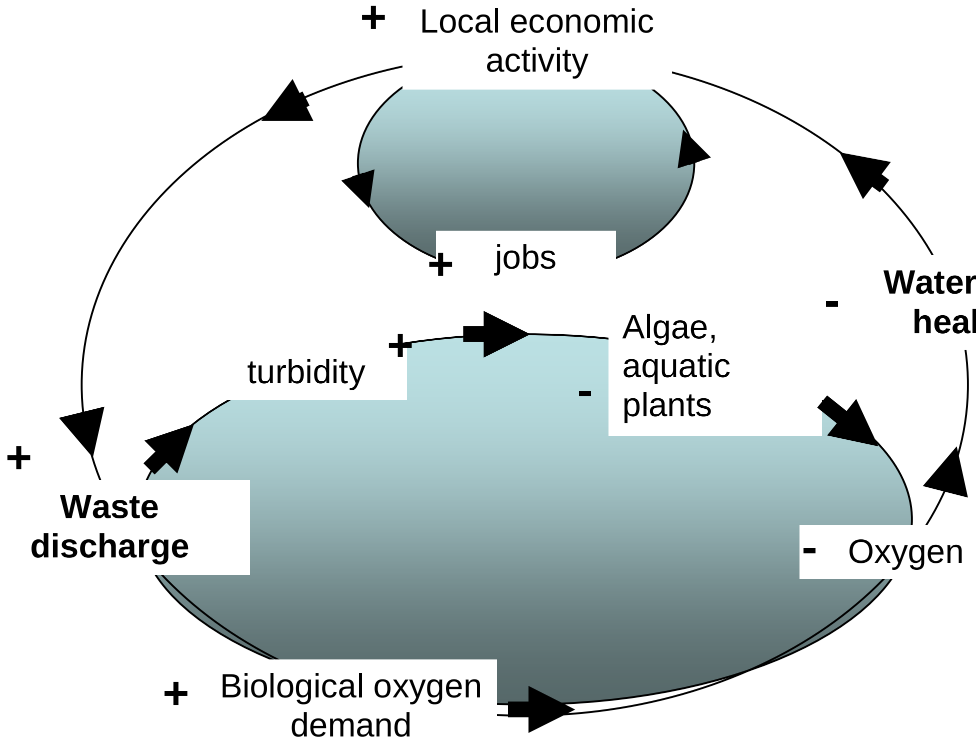

Figure 3: Causal loop model showing the integrated relationship between local economic activity, ecosystem response and waterway health.

Causal loop models are a widely used structured graphical procedure for the development of meaningful conceptual models that are then used in qualitative modelling of complex systems (Senge 1990) including environmental processes (Ford 1999), biological problems (Arquitt and Johnstone 2004, Puccia and Levins 1985) or economic and corporate policies (Morecroft and Sterman 1994). Causal loop models are suitable for furthering our understanding of environmental issues including (1) developing a reasoned overview of relevant economic, social, ecological and biogeochemical processes affecting a specified environmental condition such water quality for (2) design of relevant information gathering activities and (3) subsequent design of numerical simulation models to test strategic actions to improve the condition of the environment.

Beginning with the catchment-based schematic, causal loop modelling would facilitate a structured approach for the development of a conceptual model. By identifying the economic, environmental/ecological processes occurring within a catchment or ecosystem, or its parts, it should be possible to identify the drivers of change most likely to impact on the condition of the environment (or aspects of society).

The conceptual model shown in Figure 3, featuring linkages between water quality issues and economic activity, is based on causal loop modelling principles consistent with the development of simultaneous equations. Causal loop modelling is a special class of signed digraph theory. Signed digraphs are constructed such that arrowed links between variables are signed positive if the second variables change in the same direction. For instance, as economic activity increases then employment (jobs) will increase. Similarly, if turbidity decreases, then algae and aquatic plants increase as more light reaches the plants.

The structured conceptual model can be built up using increasing complexity as additional data and relationships between variables are explored. Those variables identified as having the greatest affect on processes within the system are those variables that must be measured reliably. In this way the conceptual model provides input to the information gathering program, including in-field sampling to further understand the processes as well as monitoring to determine the response of the system to management.

Whether causal loops or another form of modelling is used to frame and investigate our understandings of the important systems operating in a catchment, an interdisciplinary team will need and wish to go beyond the human activity patterns mentioned so far in this paper. While activity patterns are a useful starting point to consider the water cycle, these are inevitably guided by complex and abstract societal factors such as cultures, institutional arrangements and economic arrangements.

Ultimately, we are interested in distinguishing the key elements of ‘social-ecological systems’ (Berkes and Folke 1998, Carley and Christie 2002, Walker et al. 2004) with respect to the water cycle. What are the interdependencies between people and water, and other biophysical features and systems that govern water availability? How do people affect water, and does water affect people and what they are able to do? How does this occur at different spatial and social scales, from the individual, family, household and village or neighbourhood, to the catchment or region and larger scales? How are these interactions affected by values, a society’s decision-making arrangements, economic arrangements, and learning arrangements (Ross et al 2000)?

The potential to link a systems analysis powerfully with a spatial analysis, and data, is illustrated by a modelling approach taken by the Integrated Water Resources Assessment and Management (IWRAM) Project developed by Integrated Catchment Assessment and Management (ICAM) at the Australian National University with Thailand’s Royal Projects Foundation (Scoccimarro et al. 1999). This demonstrates how social, economic and biophysical modelling can be fully integrated around an identified issue. Its development proceeded from conceptual modelling to numerical estimations, using data gathered in a case study catchment in Northern Thailand, where there was conflict over surface waters and policy options were unclear. The key issue was to identify the amounts of water diverted for irrigation purposes, and the effects of these diversions on the options, decision-making and potential well-being of downstream households.

The main conceptual components of this integrated modelling approach are

- A streamflow model of the passage of water along a stream system, past numerous weirs where villages extract water for irrigation. (This model was coupled with an erosion model, and can be coupled with other biophysical models as well as considered with land cover, mapped on GIS). As the farms of each village extract water, less is left for those downstream to use.

- A combined economic and social model estimates the water taken from the streams at each village 'node', focusing on the concept of a household 'resource management unit' or RMU. Each village has a combination of such farming systems, varying according to the resources available to the household (rainfed upland fields, irrigated rice fields, or a combination of these – with various areas and land quality), and the household goals (e.g. achieving food security, or maximising cash income - affected by culture, and the varying degrees of risk associated with the people's access to resources).

The framework underpinning the IWRAM model thus considers the dynamic relationship between physical processes and household decision making.

4. Stage 4 – Applying the framework for tailored purposes

Our conceptual framework can form the basis for a number of water management (and broader development) purposes, including integrated catchment management, environmental and social impact assessment, development planning, or risk assessment. Each of these choices will require highlight on different factors, for instance integrated catchment management will require strong attention to existing and potential future institutional arrangements.

We will illustrate here the use of the framework towards risk assessment, since this is the theme of the AWRF research project.

Risk assessment

Each of the subsystems considered in building up this framework has potential risks attached. Without being exhaustive, some of these are suggested in table 2.

Table 2: Potential risks associated with water use systems

System	**Potential risks**
Drinking and domestic water	• Quantity risks – not enough water for present or anticipated future populations • Quality risks – contamination at source or at other stages, leading to human health risks, animal (e.g. stock) and environmental health risks. (This entails a need to look at risks from other sources of contamination, e.g. mining, agricultural practices, upstream waste disposal). • Risks to infrastructure e.g. natural (earthquakes, landslides) and human (under-design for the demands, lack of maintenance possibly related to expense of maintenance, accidental damage, warfare or attack).
Water in food production and consumption	• Sufficiency of water for crops, including seasonal availability and inter-seasonal cycles (droughts etc), leading to food security (famines), availability to meet export commitments, broader economic requirements. • Over-allocation of irrigation water (related to institutional arrangements) • Conflict or competition – over water and/or food supplies. • Poverty, or inequitable distributions, of water and/or food resources. • Risks to infrastructure (see above for drinking water). • There may also be risks elsewhere in the food supply system eg transport failures, market failures.
Water as part of housing and urban systems	• Infrastructure – overload, ageing, cost of maintenance, breakdown. • Relevance of infrastructure (is the technology appropriate to demands, and to capacity to finance and maintain it?) • Urban-rural competition for water. • Supply risks (adequacy of supply). • Waste risks (contamination potentially affecting this community, or others especially downstream).
Water in social and spiritual needs	• Destruction of natural or cultural values. • Visual pollution (reduction of scenic amenity). • Damage to amenity value e.g. over-visitation spoils the calming effect.
Risks associated with ecosystem needs	• Quality (pollution, erosion) and quantity (environmental flows) of water in natural environments. • Loss of biodiversity from human activities or natural disasters.
Whole-of-system risks	• Risks arising from competition between uses, for instance environmental and human needs, industrial and drinking water (contamination), agricultural and urban uses. • Cumulative impacts of water uses or deleterious practices. • Risks arising from incompatible activities along a stream network (or in use of aquifers) e.g. upstream-downstream competition for water, contamination processes. • Risks associated with temporal variability.

Once risks are identified for a given study context, these would be ordered in relation to their likely impact on the system (degree of risk, degree of impact). Both spatial and temporal risks may need to be identified. It is particularly important to take an 'integrated catchment management' view, and consider where sub-systems may conflict.

5. Customising and using the framework

We envisage this framework being customised in two key ways, either by a research team (or management team) working alone, or within a participatory process wherein a research team and other groupings such as water managers, development planners, and local communities might develop the framework to focus on issues of interest to them, and enrich the 'picture' of relevant systems together.

While the framework has been designed so far with research uses - to inform management - in mind, it could equally form a management tool to help managers assess where potential problems lie and how to address them, or a communication tool helping stakeholders to share and amalgamate their understandings of a catchment and its systems.

Lest the several levels in the framework appear daunting, we suggest it can be approached in steps that would be familiar to most teams. These steps are not necessarily sequential: it is possible to approach them in a different order, and almost certainly necessary to revisit them iteratively as decisions on one step affect previous decisions on others.

1. If the team is using a participatory process with others, design the process to include or represent those with an important 'stake' in the issues, and to be comfortable for all participants. Preferably include people who know the area chosen for study.
2. Collect local area information information, including maps, through a variety of sources and people (this is a continuing task).
3. Decide the focal *scale* of initial analysis, e.g. a catchment, but be mindful of scales above and below this where drivers may emanate, decisions can be made or effects be felt.
4. Produce a schematic diagram appropriate to the issues and scale, listing 'layers' of information that may be needed.
5. Identify focal *issues* for analysis e.g. adequacy and safety of drinking water supply, consequences of projected population growth and increasing urbanisation, impacts of intensification of agriculture, impacts of logging or industrial growth, review of policy or legislation, economic analysis. The selection of issues can use indicators such as percentage of population with access to safe drinking water, where these are available. The selection of issues can also use 'what' scenarios to encourage participants to think beyond the present, for instance 'what if migration to the capital city intensifies?'
6. Identify *time scales* for consideration (past, present, future and how far ahead; seasonal and inter-seasonal temporality?).

7. If necessary, mind map what the team needs to know about, and why (if this is not already in the framework).

    Ask ‘what affects x?’ ‘What is affected by x?’

    Rather than a general mind map, try to concentrate on *influences*.

8. Map the issues focus onto the schematic diagram (e.g. conflict between irrigation water usage and downstream rural water supply here, risk of contamination to urban water supply there).

A participatory process would probably pause at this point, and the subsequent steps take place over an extended time.

9. Construct systems conceptual models of the systems and sub-systems of interest, using causal loop modelling, Bayesian Belief Networks, Systems Dynamics, or your preferred tool. Include relevant trends and pressures, and their implications e.g. how will projected population growth or rates of urbanisation affect the current system. Consider cumulative effects of several types of trend, interactions between different parts of the system (e.g. how will population growth and demographic shifts interact with changes in farming practices within the catchment, changes in the market for a key primary product?)
10. ‘Populate’ the systems models (for different parts of the catchment if necessary) by adding stocks, flows, and trend data to key parts of the system, and their interactions. (These could be water flows, rates of water consumption, rates of agricultural production e.g. melons grown per litre of water, financial flows, projected demands).
11. Turn the framework to its intended use, for instance consider the risks inherent in the system, or the environmental and social impacts of a proposed new development or policy, or the planning needs.
12. Consider the response options and capability to address these. Advocate *integrated* response options, within local/national preferences and capacities (or achievable capacities). Avoid one-sided solutions that cause new problems elsewhere in the system.

CONCLUSIONS

The framework described here has four main elements:

- the whole of water cycle
- spatial and temporal context (catchment schema)
- systems analyses
- applications.

It is designed to be built up in stages for particular locations, issues and applications, thus users need to customise it for their needs and contexts. Its advantages are linking established approaches in integrated catchment management with a stronger focus on the water cycle and on systems analyses, and in guiding the interdisciplinary consideration that proves challenging for many research teams.

At a broad level the framework and systems understandings have precedents, such as a range of approaches in Integrated Catchment Management, interdisciplinary conceptual frameworks developed by Boyden et al for human ecology (Boyden 1992) and Ross *et al.* (2000) for understanding cities as systems, and the work of the Integrated Water Resources Assessment and Management (IWRAM) project (Scoccimarro *e. al*. 1999). Boyden et al's model considered nested scales of environment and governance, and offered a useful focus on human activities as a mediating factor between the nature of the environment and people's experience. The Ross et al. framework focuses on people-environment interactions (which can also be construed as 'social-ecological systems', after Berkes and Folke 1998, Berkes *et al.* 2003, Folke et al 2003, Walker *et al.* 2004). It relates these to different social and spatial scales (though not explicitly to specific locations) and to important societal characteristics and arrangements such as values, decision-making (governance), economic arrangements (systems of meeting needs), learning arrangements (e.g. education) and social arrangements (including social structures and processes). Meanwhile, the IWRAM framework (Scoccimarro *et al.* 1999) provides a precedent for integrating social, economic and ecological systems within a combined conceptual understanding of how people use water, with a strong capacity for combining mathematical with conceptual modelling to understand the system interactions and their vulnerabilities.

We emphasise that this conceptual framework is intentionally broad to assist research teams – possibly working in a participatory way with management organisations or communities - to think clearly about complex systems. It is a procedure for building more detailed conceptual frameworks and systems analyses appropriate to issues and places. It is not a 'final', ready-to-use framework: it is designed to be, and needs to be, customised to different uses. It is also a work in progress. The team will continue to develop the framework, both by refining systems analyses, and by improving the spatial-systems understandings through work on case studies.

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References

Abel N., Ross, H., Herbert, A., Manning, M., Walker, P. and Wheeler H. 1998. *Mental models and communication in agriculture*. Rural Industries Research and Development Corporation publication 98/140, RIRDC Canberra.

Arquitt, S and Johnstone, R. A scoping and consensus building model of a toxic blue-green algae bloom *System Dynamics Review*, 20 (2): 179-198.

Berkes, F. and Folke, C. (Eds). 1998 *Linking social and ecological systems: Management practices and social mechanisms for building resilience*. Cambridge University Press, Cambridge, UK.

Berkes, F., Colding, J. and Folke, C. (Eds). 2003. *Navigating social-ecological systems: building resilience for complexity and change*. Cambridge University Press, Cambridge, UK.

Boyden, S. 1992. *Biohistory : the interplay between human society and the biosphere : past and present.* Paris : UNESCO ; Carnforth, Lancs, UK ; Park Ridge, N.J., USA : Parthenon.

Carley, M. and Christie, I. 1992. Managing Sustainable Development. Earthscan, London.

Checkland PB.1981. *Systems Thinking, Systems Practice*. Wiley, Chichester.

Checkland PB. and Scholes J. 1990. *Soft Systems Methodology in action*. Wiley, Chichester.

Ford, A. 1999. *Modeling the Environment: An Introduction to System Dynamics Modeling of Environmental Systems.* Island Press: Washington DC.

Maslow, A.H. 1954. *Motivation and Personality*. Harper and Row, New York.

Morecroft, JDW., and Sterman, JD. 1994. *Modeling for Learning Organisations*. Productivity Press, Portland, Oregon.

Puccia, CJ., and Levins, R. 1985. *Qualitative Modeling of Complex Systems: an introduction to loop analysis and time averaging*. Harvard University Press, Cambridge, Massachusetts

Robson, C (2002), *Real World Research* (Blackwell, Oxford).

Ross H., Poungsomlee, A., Punpuing S. and Archavanitkul K. (2000). 'Integrative analysis of city systems: Bangkok Man and the Biosphere Program study. *Environment and Urbanisation,* 12, 2, 151-161.

Ross H and McGee T. K. 2006. Conceptual Frameworks for Social Impact Assessment Revisited: Interpretation of a Cumulative Effects Case Study on Lead Contamination and Economic Change. *Impact Assessment and Project Appraisal* 24,2, 139-149.

Scoccimarro, M., Walker, A., Dietrich, C., Schreider, S., Jakeman, A. and Ross,.H. 1999. Integrated assessment of water use and allocation in an upland catchment: Mae Uam, northern Thailand. *Environmental Modelling and Software,* 14, 567-577.

Senge, Peter M. 1990. *The Fifth Discipline: The Art and Practice of the Learning Organization*. New York: Doubleday Currency.

Walker, B., Holling C.S., Carpenter, SR, and Kinzig, A. 2004 Resilience, Adaptability and Transformability in Social-ecological Systems, *Ecology and Society*, 9(2) [online].