Contributing Paper

Information Needs for Appraisal and Monitoring of Ecosystem Impacts

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Dams, ecosystem functions and environmental restoration

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1. Introduction

The ecological functioning of a river ecosystem is a complex and dynamic overlay on its relatively simple physical and chemical functioning. It is these simpler aspects, nevertheless, that have globally received the bulk of funding in investigations related to development of their water resources. In the majority of countries, for instance, years if not decades of national funds have been invested in establishing a hydrological database. This has entailed creating and maintaining a countrywide network of hydrological gauging stations. We know of no country where there has been a similar level of investment in understanding the ecological nature of rivers or the hidden social costs of poorly-functioning rivers. Failure to understand and take these aspects into account in water-resource management has led to the present position where the condition (health) of rivers is deteriorating worldwide, with the overt and hidden costs to society largely unquantified.

The growing global accent on sustainable use of resources is driving a requirement for more sensitive management practices. Increasingly this is being reflected in countries' policies and legislation. High among these requirements is the placing of ecological and social investigations on the same footing in water-resource developments as engineering and direct economic ones, with the same time frame and the same structured funding. These aspects should not be seen as "extras" in water-resource development, but as key inputs to the decision-making process. Only when these inputs are routinely made will the full spectrum of costs and benefits of water-resource development options be appreciated. Giving social and ecological aspects equal weight with engineering and economic aspects will not address the enormous disparities of the past, but will at least allow a beginning to be made on developing an adequate knowledge base for the future. Similar inputs should be made to management decisions on extant developments. For instance, considerable scope exists to mitigate some of the ecological impacts of existing impoundments through the manipulation of operating rules, minor alterations to the structures or de-commissioning of dams.

In this document, we provide an outline of the ways these two additional aspects should become inputs into the decisions about proposed dams. A similar protocol would apply regarding re-structuring of the operation of extant dams or the de-commissioning of dams. The social aspects considered are those directly related to the use of river resources; wider social considerations should be incorporated through a Public Participation Process (PPP), which is not considered here. Where the term "environmental" is used, reference is being made to the combined ecological and direct social aspects.

The kinds of environmental data needed on rivers cannot be provided from a week or two of effort. With present knowledge, for instance, even after some considerable research effort, river scientists could probably only describe *trends* in river ecosystem response to management actions, and not predict the *timing* and *severity* of the response. To some extent this is likely to be true for decades to come, because of the inherent complexity of ecosystems. This should not be seen as a reason for making no effort, but rather a challenge to advance the ecological study of rivers from the descriptive to the predictive, in much the same way as was done with hydrological studies earlier this century. To do this, a long-term investment is needed, around the twin goals of enhancing our ability to predict the environmental consequences of any proposed management action, and transferring this information to decision-makers in a form that they can understand. "Rapid methods", "guesstimates" and expert opinion may be used to advise management in the short term, but the confidence in such inputs is low, and living on the capital of a paltry knowledge base and understanding of river functioning is not an option if sustainable use is the goal. To achieve such a long-term goal, some countries will have further to go than others, and for many, particularly in the southern hemisphere, there is the additional urgency that the decisions made will impact on millions of people directly dependent on the rivers for sustenance.

In order to build up an adequate knowledge base on environmental aspects for informed decision-making about dams, a series of different kinds of data collection and analyses are needed. These can be encapsulated in eight main sets of activities, grouped as follows:

a) Establishing the knowledge base
- situation assessment;
- specialist reviews and selection of representative components;
- development of a predictive capacity of biophysical responses to dam-related flow changes;
- development of a predictive capacity of social impacts of the biophysical responses.

b) Interpretation of knowledge base (decision support)
- creation of scenarios;
- establishment of a decision making process.

c) Further applications and developments of the knowledge base
- inputs to dam design;
- monitoring.

Biophysical and social scientists should carry out Group A activities, and should work closely with water managers on Group B and C activities.

2. Eight steps to informed-decision making

2.1 Step 1: Situation Assessment

A Situation Assessment (also called an Issues Assessment, Reconnaissance, Appraisal) has the objective of identifying the extent of the targeted river system likely to be affected by the dam – both upstream, downstream and in the reservoir basin – and alerting decision-makers to the likely ecological and social issues. It is usually based on existing knowledge in the form of catchment (basin) studies; demographic data; land-use data; conservation surveys; scientific, social, anthropological and resource-economic studies; and relevant national law and international treaties. An aquatic or environmental scientist who is experienced in water-resource management should do Step 1, which could take one to several months depending on the complexity and size of the system.

A critical assumption is that the literature exists. If it does not, this is where a country needs to begin developing effort. If it does, almost invariably it will not be sufficiently comprehensive to allow management of the river system on a sustainable-use basis. For instance, there may be no comprehensive species list of riverine species (even less their life-cycle requirements); no knowledge of the presence of rare and endangered species; poor understanding of how different or similar the river is to neighbouring ones (and hence questionable validity of extrapolating data from better-known to poorly-known systems); no understanding of channel characteristics and which reaches are flow-sensitive; and only a vague awareness that people use the river's resources with an often mistaken impression of the extent of this use.

The output of this step is essentially a literature review, reflecting the present knowledge base on the river, key issues of concern, key aspects that need further investigation, and the disciplines that should be involved in such investigations (Table 1).

Table 1: Knowledge base and key aspects to be reported on in the Step 1 literature review

Knowledge Base/Key Aspect	Examples/Comment
Extent of affected area	Include inundation area of the dam. Also include estuary and near-shore environment if relevant.
Present and projected future demographics and water and land use	Not in detail – simply to create an awareness of the status of the catchment.
Present condition ("health") of the river ecosystem, with reasons	Compare to reference (natural) condition.
River importance	Social, ecological, economic; local, regional, national, and international.
River resources being used	Category 1, 2 and 3 users*.
Environmental issues of potential concern, each linked to its contribution to River Importance	E.g., rare and endangered species, pest species, RAMSAR sites, National parks, groundwater levels, health risks, uniqueness of the river, important resources used by the PAR.
Identification of the disciplines for the investigation	see Step 2.

*Category 1 users are those directly dependent on the river for sustenance, here called Population at Risk (PAR).

*Category 2 users are all others using river resources, such as irrigation schemes, recreation businesses and urban areas.

*Category 3 users are the wider – possibly global – community, through national laws and international treaties.

2.2 Step 2: Specialist reviews and selection of representative components

A range of specialists, identified in Step 1, is needed to provide a comprehensive description of the affected area. A core group of disciplines provides the most direct flow-related information (Table 2), and would be essential for producing an adequate knowledge base for any river. Additional specialists (Table 2) may be included as relevant, to provide additional ecological perspectives, or river-related social perspectives.

Table 2: Disciplines involved in Step 2

Specialist	Knowledge input
Core group	
Hydrologist	The river's flow regime - volumes and distribution in space and time - preferably at daily time-step.
Fluvial geomorphologist and sedimentologist	Channel patterns and types; movement of sediments through the system; the relationship of all these to flow.
Hydraulic modeller	The conveyance of water along the channel - velocities, depths, areas and features inundated at different flows.
Water chemist	Past and present water quality; likely future problems related to flow changes.
Sociologist	Identification of the PAR and of all river resources – including drinking water – being used; other river concerns of the PAR (e.g., religious, cultural). Use of terrestrial resources in the dam basin should also be identified.
Ecologist (flora)	Aquatic and particularly riparian plant communities: by species, linked to zones of different inundation or hydraulic stress; plants used as a resource; biodiversity issues. Terrestrial plant communities in the proposed dam basin.
Ecologist (aquatic invertebrates)	Invertebrate species and communities; rare species, pest species; as indicators of health, longitudinal river zonation and ecosystem functioning; biodiversity issues.
Ecologist (fish)	Fish species and communities; rare species; as food source; as indicators of wider issues of river health and functioning (e.g., longitudinal connectivity); biodiversity issues.
Terrestrial ecologist	Birds and terrestrial wildlife in the dam basin, and those dependent on the downstream river ecosystem.
Additional group	
Ecologist (herpetofauna)	As for fish.
Ecologist (aquatic mammals)	As for fish.
Anthropologist	Importance of the river in the life of the PAR.
Public Health	Present health profile of the PAR; likely future flow-related changes.
Animal Health	As for Public Health.
Resource economist	Amount and value of resources used by PAR. Values for Category 2 and 3 users should be ascertained through the PPP.

Investigations by the specialists provide an informed perspective that would not be possible in Step 1. It is an essential step, but one where science is perhaps most likely to be trivialised. There may be the temptation to cut costs, use inexperienced individuals, or assume that one or two generalists can do the job. Step 2 should be undertaken by experienced professionals in each discipline, most of whom would probably require a minimum of one field survey, or two at different seasons, plus appropriate office/laboratory time. Obviously, the more investment in the exercise, the higher the confidence in the results. The specialists' outputs of Step 2 should be, *inter alia*, comprehensive descriptions of the river ecosystem from their perspectives (Table 3), together with a well-argued selection of river reaches, river sites, social areas and key biotic species or communities that can represent the study area as a whole. These will become the focus of Step 3. Where relevant, the specialists should also indicate the impact to terrestrial ecosystems of areas that will be inundated by the dam reservoir.

Table 3: Examples of possible outcomes of Step 2. (This is not an exhaustive list).

Specialist	Product 1	Product 2
Geomorphologist/ sedimentologist	Delineation of lengths of river with different channel type, gradient and sediments	Reaches and sites to represent the study area as a whole.
Ecologist (all)	Delineation of lengths of river with different biotic characteristics. Biotic communities of river and proposed dam basin described. Rare species identified.	Key species identified, with reasons.
Sociologist	Delineation of catchment into zones of direct river use and non-use. Direct areas allocated to biophysical zones as above.	Villages to represent PAR. in each zone (including the dam basin).
Ecologist and sociologist	River and terrestrial resources used by PAR identified, and relevant biophysical specialists incorporate these into Step 4.	
Riparian ecologist	Bank vegetation delineated by vertical and horizontal zones of inundation. Plant communities in each zone described.	Key species of social importance included in Step 4.

2.3 Step 3: Developing predictive capacity of biophysical responses to dam-related flow changes

This step, of all eight, represents the major investment in time and effort. In most countries it still has to happen to any structured and comprehensive extent. Without the knowledge base developed in this step, most ecological advice on river management will be, at best, informed opinion. Developing the right knowledge base is difficult; it is all too easy to gather data in a familiar way without structured thinking of whether or not these can provide the required management answers. New kinds of data are needed, and specialists must be amenable to approaching their disciplines from new perspectives and devising new, relevant ways of studying rivers.

The step requires an applied-science mindset, and a commitment to inter-disciplinary, problem-solving research. Whilst much progress could be made in routine studies at tertiary education institutions, there may be no guarantees that the right kinds of data are collected as and when needed for development projects. The disciplines advising on sustainable river use are so specialised, developing so fast and experiencing such a rapid growth in demand, that special efforts need to be made to provide sufficient numbers of the right kinds of expert. A major step forward would be the creation of national or regional centres of expertise, where techniques are developed, young scientists trained and world developments tapped into. Such centres would provide pools of specialists available to guide appropriate investigations within their regions.

The costs in time of developing such a predictive capacity for any river system would be a minimum of two years and preferably five years. This does not necessarily imply full-time employment of specialists of all disciplines listed in Table 2 over these time spans. Rather, it allows for selected nodes of activity linked to specific seasons or events, in order to obtain some insight into the characteristics of such features as flood events, biotic tolerance ranges, or the levels of both intra-annual and inter-annual variability in data sets. Each specialist would advise on the schedule best suited to meeting her or his objectives. Even after the preferred five years, a bare minimum of understanding on the functioning of such dynamic systems would exist, necessitating ongoing monitoring after the development (Step 8).

The financial costs involved in this step may seem high compared to past expenditure in this aspect, but will probably account for far less than 1% of total project costs. Most costs will be centred in the pre-construction phase (Steps 1-5) and after the dam starts operating (Step 8), although there should also be an Environmental Management Plan (EMP) in operation during dam construction. Pre-construction and EMP costs should be formalised as part of project costs, and post-operation monitoring costs should be funded from the financial benefits derived from the project.

Development of predictive capacity involves the use of specially-constructed data sets, models and various analytical tools (Table 4). Models are calibrated using measured data and then used to simulate the outcome of future unmeasured events. They have the weakness that only outcomes linked to measured data sets will be simulated, and so unusual, extreme responses of a highly stressed river system may still be unpredicted. However, their use in scenario creation (Step 5) is invaluable. Analytical tools provide ways of using measured or simulated data to produce specific information. Such specific data sets may include, for instance, those that specify conditions needed for a certain fish species to spawn or how water quality differs between the rising and falling arms of a flood hydrograph.

Physical and chemical forces (hydrological and sediment regimes; hydraulic forces, chemical and temperature regimes) drive the ecosystem, creating a template upon which the biological system reacts. All of these components have to be addressed. Attempts to exclude any may well lead to incomplete answers, large areas of uncertainty, or delay as excluded components are added later. Cost-saving - if essential - should probably rather address less research per discipline than fewer disciplines, but then highly experienced individuals should be used. However, the level of confidence in the information and predictions arising from such studies almost always increases with increased financial investment in them. Thus, it is essential that a balance between cost and appropriate levels of research effort be sought. The use of inappropriate levels of research could end up being a false economy.

Table 4: Tools and kinds of data required for developing predictive capacity of flow-related river changes

Discipline	Tools
Hydrology	Hydrological models that can produce daily hydrographs for any location in the river system, under natural, present and potential future conditions, and can analyse these in ways required by ecologists. Daily systems models that can simulate potential releases of environmental flows. Reservoir-yield models that can incorporate all water demands, including environmental flow releases linked to daily current-climate indicators.
Geomorphology Sedimentology	Sediment models and channel-change models that can predict and quantify flow-related channel changes in terms of their impacts on physical conditions and thus also on habitat for river biotas.
Hydraulics	Inundation models for the reservoir; inundation models linked to daily hydrographs for the river channel, floodplains, wetlands, estuary and secondary channels, so that the percent of time that any feature or species is inundated, and the related water velocity, can be predicted;
Water quality	Daily records – hourly for flood-event sampling – at selected representative points, using data loggers where appropriate; key variables measured should always include temperature and any other variable likely to be affected by the dam; microbiological sampling for relevant parasites and diseases; stratification and eutrophication models for the reservoir;
Vegetation	Linkage of inundation zones to daily hydrographs, so that past, present and predicted future inundation/exposure times can be given; multivariate analyses of distribution of plant communities along different environmental gradients (including inundation) to establish trends for predictive purposes; phenological (life cycle) studies linked to inundation zones, to understand how plants react to water-stress;
Aquatic and water-dependent fauna	Multivariate and other analyses of distributions of animal communities along environmental gradients; habitat requirements of key species; physical and chemical tolerance ranges so that the biological outcomes of physical and chemical changes can be predicted
Ecologists	Environmental flow assessment methodologies, to manage all the above kinds of data in a structured process, leading to scenario development (Step 5).

2.4 Step 4: Predicting social impacts of the biophysical responses

Society as a whole bears the social and economic burden of poorly-functioning rivers, in a number of ways. Most of these costs should be captured, and passed to the decision-making process, through the PPP running parallel to the steps described here. In this step, only the direct costs to the PAR are addressed. The PAR may gather river resources for food, building material, drinking water, firewood, medicines, and other similar sustenance purposes. Some may derive a modest income from the resources they collect. Many cultural and religious sites may be linked to rivers, as may recreational activities. The PAR may well consist of the poorest and most vulnerable of human communities and yet, because of their close ties with the river, the losses that they suffer when it is dammed may well be the most severe. All river-related aspects may change, as may the health profile of the PAR and their livestock.

A structured process for describing the potential extent of their loss, and for providing fair mitigation and compensation, is one of the newest and most urgently needed inputs to decision-making on projects involving dams. These losses are largely unquantified to date, but the little data that we have suggest that with a large PAR and a dam operating for maximum abstraction, they could amount to a significant percentage of the total cost of the dam's construction, *per annum.*

In Step 4, the present river-use and health profiles of the PAR and their livestock are quantified, and possible flow-related health risks are identified. The tangible values (that can be costed) and intangible values (that cannot be costed) of all relevant river attributes are recognised. An assessment of the present economic value or cost of replacement of all tangible attributes (e.g., thatching grass; fisheries, religious and cultural sites) is made. In Step 5, these data are linked to predictions of biophysical changes (Step 3) in the development of scenarios.

Intangible river values recognised or used by the PAR (e.g., beauty; spiritual sites; the "silent services" such as water purification) should also be a structured input to the decision-making process. These values can be included in the scenarios, but will not have an economic value attached.

2.5 Step 5: Creating scenarios

From the preceding steps, scenarios can be created that present a series of future options for the decision-maker to choose from. As a first stage in scenario creation, the decision-maker should indicate, in discussion with the river specialists, the kinds of scenarios that would be needed for consideration. *Inter alia*, these can be ones where:

- a volume of water is required as yield, in which case the scenario can describe how the remaining water can be managed as a "least-damaging" flow regime;
- a valued species, community or river feature should be protected, in which case a flow regime to achieve this would be described;
- river rehabilitation downstream of an extant dam is required, in which case the best that can be achieved with the design limitations of the dam can be described;
- the priorities of the competing users are defined, in which case the resulting flow regime and its effect on river condition are described.

In addition, the "no development" scenario should always be included.

Once the scenarios have been decided on, the biophysical consequences of each can be described (from Step 3), the social impacts detailed (from Step 4), and the economic implications quantified (from Step 4). Compensation for the direct losses incurred can be costed, as can acceptable mitigation measures, such as establishment of wood-lots to replace lost firewood sources.

At completion, each scenario should have the following detailed components:

- a detailed flow regime in the river, together with its volume and percent of Mean Annual Runoff;
- the river condition that would result from this flow regime;
- the impacts (positive and negative) on the PAR of this river condition;
- the economic implications of these social impacts;
- any other impacts (positive and negative) associated with the dam.

2.6 Step 6: Establishing a structured transparent decision-making process

Agreement should be in place before the development of the scenarios, on a structured, transparent decision-making process for deciding between them. The scenarios provide five inputs to this process, as listed in Step 5. Other vital inputs are:

- the findings of the PPP, which should include reactions to the scenarios;
- the economic and other implications of different yields of marketable water, using agreed costing processes;
- the intangible costs, if not included in the scenarios;
- an assessment of the bigger picture. This should include aspects of water demand management, structured consideration of the most advantageous use of water in the system as a whole, and the predicted impacts of global climate change on the ecosystem of concern. Several different rivers may be under considerations for any one proposed development and the knowledge base on each one should be adequate (Steps 1-4) to allow a defensible assessment of where the dam(s) would cause least damage.

A first step in the process would be to agree on how all the inputs should be used and managed. Following that, the scenario that provides the most acceptable overall option should be selected. This will provide a broad idea of future river flows, river condition and consequent impacts. The scenario can then be refined for acceptance and implementation when the dam comes on line.

2.7 Step 7: Inputs to dam design and the Environmental Management Plan

Two major environmental activities should take place between when a scenario is agreed upon and when the dam becomes operational. These are not strictly information needs for decision making in the same way as previous steps, but are included for completeness. The first of these is input from the scientific team on dam design that can minimise the impacts of the dam on the river. Dam features such as off-takes that can release floods (not at the base of the dam, but higher, in better quality water), may increase construction costs. In the past, there may have been pressure to exclude such features for this reason. In the future, dam design should not begin in earnest until after Steps 5 and 6 are completed, by which time the decision has already been made on the chosen outcome in terms of river flows. Dam design should then be geared to help achieve this scenario.

The second activity is creation and implementation of an EMP for the construction and operation phases. Ecological and social aspects related to the impact of construction activities, and control of these impacts, should be included in the EMP.

2.8 Step 8: Monitoring

During dam construction, a programme of monitoring for downstream ecological and social impacts should be maintained as part of the Environmental Management Plan. When the dam begins operation, a long-term monitoring programme should be initiated. The specialists involved should be some or all of those who participated in Steps 2-5. They should be required to design an appropriate monitoring plan that:

- can distinguish flow-related change from flow-unrelated change;
- can monitor for short-term and long-term changes;
- can incorporate several years of testing and iteration to link releases optimally to current climate;
- can distinguish trends in measured attributes from inherent system variability;
- can record if the agreed environmental flow is being met in the river;

- can illustrate if the river condition predicted in the chosen scenario is being achieved.

The monitoring programme should be structured so that there is regular:
- independent assessment of the value of each monitoring activity;
- analysis of, and report back on, the collected data.

Based on monitoring results, the decision-making process should be able to act on non-attainment of the predicted river condition by adjusting either:
- the desired river condition, or
- the environmental flow release.

3. CONCLUSION

The difficulty of managing inherently variable ecosystems with an inadequate knowledge base of their nature and functioning will be with us for decades to come. Adequate development of that knowledge base is the key to sustainable use of rivers, and is possible. This would be a substantial undertaking. National and international investment in carefully designed studies would be needed, perhaps guided by regional centres of expertise. Importantly, all concerned with river management would need to accept the concept of sustainable use, and be willing to work in a supportive multi-disciplinary framework toward that goal. The investment and effort required is not trivial, but neither is the importance of achieving this goal. The major endeavour of the next century will be better use of the Earth's resources. Aquatic ecosystems rank among the highest of those resources.