DEVELOPMENT OF DRIFT, A SCENARIO-BASED METHODOLOGY FOR ENVIRONMENTAL FLOW ASSESSMENTS

by

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EXECUTIVE SUMMARY

Introduction

DRIFT (Downstream Response to Imposed Flow Transformations) is a new methodology under development for assessing the flow requirements for maintenance of rivers (environmental flows – EF) that are subject to water developments. It has six important attributes. First, it provides an holistic approach to EF assessments, in that it addresses all parts of the intra-annual and inter-annual flow regime, and all living and non-living parts of the river ecosystem from source to sea. Second, it is a scenario-based approach, combining data, experience from a multi-disciplinary team of specialist river scientists, and any other local knowledge on the river of concern, to provide predictions of how the river could change with flow manipulations. Third, it further predicts the social and economic impacts of these river changes on common-property subsistence users of the river's resources. Fourth, its outputs comply with the requirements of the South African Department of Water Affairs and Forestry for use in its management of aquatic ecosystems (Resource Directed Measures - RDM). Fifth, all the data and knowledge used in compilation of the scenarios are stored in a database that can be used to create any number of scenarios and that also acts as a resource in its own right on flow-related responses of rivers. Finally, it is grounded in a growing range of custom-built software that allows much of the application of DRIFT to be automated. This report documents the most recent progress in the development of and conceptual basis for DRIFT.

The project's final objectives (Chapter 1), after amendment in steering committee meetings in October 2000 and October 2001, were to:

- have a paper on DRIFT accepted for publication in an international scientific journal;
- develop the DRIFT database facility;
- liaise with two partner projects and write two of the three reports emanating from the parallel application of DRIFT, the Building Block Methodology (BBM) and the Flow-Stressor Response approach (FSR);
- support development of the DRIFT hydro software;
- develop the concept of generic lists for use in DRIFT applications;
- strengthen the subsistence component of DRIFT.

The agreed products of the project were:

- the scientific paper on the DRIFT methodology;
- a scientific paper on the DRIFT database facility;
- chapters in this final report on generic lists and the subsistence component;
- a comparative report on the joint application of the three methods.

The two scientific papers

The fundamental nature and concepts of DRIFT are introduced in a paper that is presently in press with the international journal Rivers Research and Applications (Chapter 2). The four modules of DRIFT are explained: 1) *biophysical:* data on the river are gathered in order to develop predictive capacity of how it would change in response to flow changes 2) *subsistence:* data on subsistence users of the river are gathered, in order to develop predictive capacity on how they would be affected if the river changed 3) *scenario-building:* scenarios (options) are compiled, based on potential future changes in river flow, illustrating a range of ways in which the river could change and the range of impacts this could have on subsistence users 4) *socio-economic:* the compensation and mitigation costs of these impacts are computed. In parallel with these activities, but outside the DRIFT process, continual consultation with, and participation of, all other stakeholders is recommended and outlined, as is a macro-economic assessment of the scenarios in terms of their regional/national implications.

The development of the DRIFT database and scenario-building facility, DRIFT-SOLVER, is described in a paper presently in press with Water SA (Chapter 3). DRIFTSOLVER contains an integer linear programming MCA (multi-criteria analysis) method, which generates optimally distributed flow scenarios for different total annual volumes of water. Also described is DRIFT CATEGORY, which facilitates evaluation of these scenarios in terms of river condition.

Generic lists

Generic lists (Chapter 4) were proposed as an aid for guiding the multi-disciplinary team in its considerations, and to facilitate the orderly input of information into DRIFT-SOLVER. The lists consist of river variables that are important in ecosystem functioning, and sensitive to changes in flow by increasing or decreasing in some way (e.g. in number, area or concentration). In a DRIFT workshop, each team member first compiles her/his list and then, for all flow changes under discussion, describes the consequences for all items on their list. The lists are thus essentially memory guides. It is anticipated that initially the generic list for each discipline will be relevant to the river being considered, but might eventually, after use and adaptation with many rivers, become truly generic in that it could contain all aspects of that discipline that might be important in flow management of any river.

Later development emanating from these generic lists is envisaged. An expert system could evolve that provides some degree of structure on linkages between lists for different disciplines. The structure could possibly take the form of items on generic lists linked by processes that could cause them to change. For example, an increase in the abundance of sand (Sedimentology generic list item), due to a flow change, could lead to a *process* of sedimentation, which in turn could cause a reduction in the number of interstitial spaces (Geomorphology generic list item). This leads to a *process* of habitat change, causing a decreased abundance in the riffle-dwelling species assemblage (Macro-invertebrate generic-list item). Such logic pathways could be recorded, to allow re-assessment as knowledge increases. A possible final stage of development might be the ultimate complex link-up of lists/disciplines in a kind of holistic model that predicts how the whole ecosystem could react to flow changes.

Chapter 4 provides a draft generic list for each main discipline involved in an EF assessment: sedimentology, fluvial geomorphology, water quality, vegetation, aquatic invertebrates, fish, and subsistence use.

Subsistence use

Balancing the utilisation (development) of aquatic ecosystems for various human needs with the protection of these ecosystems, so that they can continue to be used by present and future generations, is one of the central challenges in water-resource management. EF assessments are increasingly being recognized as a valuable tool in water-resource management for this purpose. They provide the other side of the picture: the ecological and social implications linked to the benefits provided by the water-resource development. In Chapter 5, the effects of such developments in terms of their impacts on subsistence users of the rivers, and particularly those impacts associated with large dams, are reviewed. Six case studies are then provided of EF assessments that have included social studies, and the lessons learnt are summarised.

It is concluded that the impact of large water-resource developments on riparian communities is little understood, but emerging evidence suggests that the existing and potential impacts of the loss of aquatic resources are high. It is thus crucial that the downstream impacts of a water-resource development be clearly documented or, in the case of a proposed development, predicted. Without an understanding of the actual or potential impacts, and their long-term social implications, the information supporting, and rationale behind, decisions relating to such developments, are essentially flawed. The EF methods now under development in South Africa allow prediction of both the biophysical and socio-subsistence impacts of such projects, which is a first step toward a more holistic approach to decision making.

As yet, there are relatively few examples of sociological studies contributing to EFAs in this manner. There are even fewer where the decision-making process is sufficiently transparent to enable an assessment of the extent to which the results of the EFAs assisted in, or influenced, the final decision on the operation or construction of a water-resource development. The ones that have been completed have attracted a disproportionate amount of attention and the trend is probably toward their more extensive application.

A relatively standard set of procedures and protocols could facilitate incorporation of sociological data into EFAs, and a first attempt at compiling such a list is provided in Section 5.5. This is intended to stimulate discussion on the possibilities for and approach to the development of a set of procedural guidelines for the sociological module of an EFA.

Parallel application of three EF assessment methods

Three EF methods, the Building Block Methodology (King & Louw 1998), DRIFT, and the Flow-stressor Response (O'Keeffe *et al.* 2002) were applied to the same river system (the Breede River), using the same specialists and data (Chapter 6). The objectives were to:

- update all involved in the exercise as to the nature and latest developments of the three methods;
- assess the advantages and disadvantages of each method and compare their outputs;
- implement, and contribute towards the development of, the FSR method;
- assess how the methods could be amalgamated into one or, alternatively, describe the circumstances in which each could be used.

The methods were evaluated in terms of the following attributes:

- their context in terms of EF assessments and the South African Ecological Reserve for rivers;
- overall approach;
- use of hydrological data;
- steps in the flow assessment process;
- costs;
- outputs;
- compatibility of output with DWAF's Reserve requirements;
- overall performance, using DWAF criteria.

The conclusion was that DRIFT and the BBM have similar costs and produce similar results in terms of percentage of Mean Annual Runoff required for a specific River Management Class. The BBM is poorly suited to scenario development, however, and for this reason and others is falling into disuse as per its manual. A Desktop Rapid method has emerged from it that is now used extensively. FSR is not a full holistic approach, but addresses only low flows, working through excising that part of the BBM and inserting new concepts and routines. All three methods meet the requirements of the RDM Directorate of DWAF in terms of output, and FSR and DRIFT are designed to produce multiple scenarios. DRIFT scored most highly for most criteria by which the methods were judged, emerging as a rigorous approach to EF assessments with similar costs to the other methods but with highly structured and transparent data collation and scenario-development phases.

A suggested way forward is outlined. This includes strong support for the following:

- an investment in the comprehensive EF methods in priority, high-conflict catchments, in order to build up the knowledge base and continue development of the methods;
- development of the rapid EF assessment methods, for use in other catchments for Reserve determinations;
- structured monitoring of rivers with EF allocations, to quickly enhance understanding and increase the confidence of predictions on flow-related river changes;
- exploitation of the ground-breaking work in this field done in South Africa through vigorous international marketing;
- investment in the science of river-condition management classes, so that they become a scientifically defensible tool for measuring and managing river condition;
- structured support for managers from the scientific community for the largest and most difficult of any of the challenges faced in this field – successful implementation.

Conclusions

DRIFT meets all the requirements of the RDM Directorate of DWAF in terms of outputs from a comprehensive assessment of the Ecological Reserve (Chapter 7). It has approximately the same time and personnel costs as other methods presently used in Comprehensive Reserve determinations, with the added advantage that it contributes to a growing knowledge base through its detailed database of flow-ecosystem links for every river to which it is applied. The database also acts as an implementation tool, through its ability to quickly create many detailed scenarios of flow-change/ecosystem-response. Several additional attributes are listed in Chapter 7.

Recommendations

The following recommendations are made.

1. Continue development of DRIFT and its knowledge base, through applications in comprehensive assessments of the Ecological Reserve. After about 15 applications of the BBM in real water-resource projects it was felt that South Africa had a method that worked and for which a manual could be written (King *et al.* 2000). DRIFT sources the same kinds of information as the BBM but uses the data in a different and more sophisticated way. This, and the various sets of DRIFT software, need further development through application as a part of real water-resource projects.

2. Transfer the DRIFT database from Excel to a Delphi software package and further develop it, to provide the following features:
   - protection of the database;
   - incorporation of new data and updating of scenarios without losing the original data;
   - generic-list items selected from drop-down lists;
   - incorporation of the new DRIFT hydro software, to form a single package;
   - a new format to ensure an attractive and user-friendly product.

3. Develop further the database, to include the socio-economic aspect of DRIFT applications.

4. Develop further the generic lists to provide lists that can be used in any South African river, and explore their potential as the basis for an expert system.

5. Liaise with current DWAF work on river management classes to ensure compatibility between these and DRIFT river classes.

6. Initiate exploration of the possibilities and limitations of applying DRIFT to other types of rivers, such as ephemeral or intermittent systems and/or large floodplain rivers.

7. Finally, South Africa's expertise in the field of EF assessments is potentially highly marketable. It is strongly urged that the country act now to take advantage of this whilst other countries are still learning their way into this field.

Capacity building

The parallel application of three methods to the Breede system provided a major training opportunity. In a mentoring approach, most major disciplines (hydraulics, vegetation, sedimentology/geomorphology, invertebrates) were represented by a senior specialist experienced in EF assessments and a junior specialist. In addition, two scientists were introduced to, and helped run, the DRIFT process, and the water-quality discipline was represented by a large group working in a team-building exercise.

Rodney February and Bruce Paxton received additional training and experience in two aspects of EF assessments: subsistence use and generic lists respectively.

Capacity building using a mentoring system is an excellent means of speeding up the training of new specialists. It is most effective if recognition is given that productivity of the mentor will decline in other areas whilst aiding in such training. At present, capacity building is often simply added as an extra requirement without any reduction in expectation of other outputs. This can result in unstructured and inadequate training by a mentor and consequent disillusion of the trainee; or 'capacity-building fatigue' from a mentor attempting to provide excellent training whilst still meeting all other commitments; or unease in a mentor who is focussing on capacity building and is aware that the other commitments are not being met at previous standards. There is a real danger of the quality of scientific research being threatened because senior researchers are becoming overwhelmed by ever-increasing demands from a range of funder, university (or equivalent institution), and management sources, and yet the country needs their original thinking as well as their mentoring skills. It is suggested that a more structured approach to capacity building is crucial in the aquatic sciences, in order to increase the number of trained people whilst also providing their mentors with time to proceed with in-depth research.

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Alison Joubert of the Department of Statistical Sciences, University of Cape Town co-authored Chapter 3 and was instrumental in the developments documented therein. Theo Stewart of the same department reviewed the MCDA procedures reported in that chapter. Charles Pemberton of Southern Waters, assisted in the compilation of the early DRIFT databases.

Jay O’Keeffe, Denis Hughes and Caroline Palmer of the Institute for Water Research at Rhodes University, and Delena Louw of IWR Source to Sea, assisted in the dual application of the BBM and DRIFT on the Breede River.

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LIST OF ABBREVIATIONS

DRIFT	Downstream Response to Imposed FlOW Transformations
IFIM	Instream Flow Incremental Methodology
EFA	Environmental Flow Assessment
IUCN	International Union for the Conservation of Nature
RBA	Rapid Bio-Assessment
DO	Dissolved Oxygen
TSS	Total Suspended Solids
BRBS	Breede River Basin Study
MAR	Mean Annual Runoff
PES	Present Ecological State
DWAF	Department of Water Affairs and Forestry
MCA	Multicriteria Analysis
BBM	Building Block Methodology
CI	Chief Interviews
CRES	Center for Natural Resources and Environmental Studies
EF	Environmental Flow
HHI	Household interviews
IDA	Institute for Development Anthropology
LHWP	Lesotho Highlands Water Project
PAR	Population at Risk
ppm	Parts Per Million
PPP	Public Participatory Process
PRA	Participatory Rural Appraisal
RRA	Rapid Rural Appraisal
SRBMA	Senegal River Basin Monitoring Activity
SRUI	Specific Rive User Interviews
UCT	University of Cape Town
US EPA	United States Environmental Protection Agency
WCD	World Commission on Dams
WHO	World Health Organisation

1. INTRODUCTION

1.1 Background

South Africa's 1998 Water Act recognises two rights to water: for basic human needs and for protection of aquatic ecosystems. The latter has been named the Ecological Reserve and is used to reserve water for maintenance of river systems where flow regimes have been or may be modified by land or water developments. Under the new Act, three levels for defining the Ecological Reserve are recognised: a Planning Estimate, a Preliminary Reserve and the Reserve. The Building Block Methodology (King *et al.* 2000a) was developed in South Africa for helping guide definition of the Full Reserve, where the greatest resolution of studies and recommendations is required. With its development and application during the 1990s several shortcomings became apparent. Some of these could be overcome by adjusting the details of the methodology, but some were inherent in the approach.

The two main inherent shortcomings were as follows.

- It is a prescriptive approach. A Desired State for the river (now called Ecological Management Category) is initially defined, and a flow regime to achieve and maintain this is then described. As the thrust of the application was to justify this one flow regime, it does not lend itself to answering management questions about the consequences of not supplying parts of that flow regime.
- The component dealing with subsistence use of the river was weak, and did not lend itself to economic evaluation of the costs of a water development in terms of lost natural resources.

Recognising these shortcomings, a new approach began development in the mid-1990s. Named DRIFT (Downstream Response to Imposed Flow Transformations), it is a scenario-based approach with strong biophysical and socio-economic components. The biophysical component is used to predict how the river ecosystem will change when flows change. The socio-economic component is used (where relevant) to predict how common-property subsistence users of the river will be affected by changing river condition.

This WRC project report details the continuing development of DRIFT. The project began in January 2000 and finished in December 2002.

1.2 Project objectives

The original project objectives were to:

- review past applications of DRIFT
- further develop the hydrological, hydraulic and water-quality components to the extent that is possible;
- write a draft manual for the application of DRIFT;

- apply DRIFT in real water-resource projects;
- strengthen the social and economic components of DRIFT;
- create a data-base and expert-system shell;
- create and run a training course on DRIFT.

After the project was approved for funding, the Water Research Commission (WRC) requested that it be carried out in close liaison with two other projects that were also addressing the Ecological Reserve:

- The development of a computer-based DSS for quantifying the components of the Ecological Reserve (Profs Denis Hughes and Jay O'Keeffe of Rhodes University).
- Communication about water quality in the Ecological Reserve (Prof Carolyn Palmer of Rhodes University).

Following discussions at the first steering committee on 24 October 2000 and through the work programmes approved by the steering committee on 24 October 2000 and 15 October 2001, amendments were made to the project objectives. There were two main reasons for the amendments. First, it is a requirement of the Department of Water Affairs and Forestry (DWAF) that any new method for environmental flow assessments had to be published in the international scientific literature before it could be used in South Africa, thus it became imperative to achieve this. Second, it was agreed with DWAF and the WRC that there should be a joint application of the BBM and DRIFT on one river with the same team of specialists, in order to compare the methods and their outputs. Subsequently, a third method – Flow-Stressor Response - was also brought into the joint application by the partner projects, and all three were applied.

The final set of objectives for the project thus became to:

- have a paper on DRIFT accepted for publication in an international scientific journal;
- develop the DRIFT database facility;
- liaise with the partner projects and write two of the three reports emanating from the dual application of the three methods;
- promote development of the DRIFT hydro software in whatever way was possible;
- develop the concept of generic lists for use in DRIFT applications;
- strengthen the subsistence component of DRIFT.

1.3 Project products

The agreed products of the project were:

- the scientific paper on the DRIFT methodology;
- a scientific paper on the DRIFT database facility;
- two reports on the joint application of the three methods;
- chapters in this final report on generic lists and the subsistence component.

1.4 This report

After this introductory chapter, Chapters 2 and 3 contain the two scientific papers. Chapter 4 describes current understanding and use of the generic lists, with an important intellectual contribution from Prof. Angela Arthington and her colleagues from Griffith University in Australia. Chapter 5 summarises all located literature on the downstream affects of dams on common-property subsistence users of rivers. Chapter 6 is the third report in the series on the joint application of methods, and Chapter 7 closes the report with Conclusions and Recommendations.

2. A SCENARIO-BASED HOLISTIC APPROACH TO ENVIRONMENTAL FLOW ASSESSMENTS FOR RIVERS

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2.1 Publication details

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2.2 Abstract

Sustainable use of river ecosystems requires that they be managed holistically. This paper describes an holistic methodology, DRIFT, for advising on environmental flows for rivers targetted for water-management activities. DRIFT's basic philosophy is that all major abiotic and biotic components constitute the ecosystem to be managed; and within that, the full spectrum of flows, and their temporal and spatial variability, constitute the flows to be managed. The methodology employs experienced scientists from the following biophysical disciplines: hydrology, hydraulics, fluvial geomorphology, sedimentology, chemistry, botany and zoology. Where there are subsistence users of the river, the following socio-economic disciplines are also employed: sociology, anthropology, water supply, public health, livestock health and resource economics.

DRIFT is a structured process for combining data and knowledge from all the disciplines to produce flow-related scenarios for water managers to consider. It consists of four modules. In the first, or biophysical module, the river ecosystem is described and predictive capacity developed on how it would change with flow changes. In the second, or socio-economic module, links are described between riparian people who are subsistence use of river resources, the resources they use, and their health. The objective is to develop predictive capacity of how river changes would impact their lives. In the third module, scenarios are built of potential future flows and the impacts of these on the river and the riparian people. The fourth, or economic module, lists compensation and mitigation costs.

DRIFT should run in parallel with two other exercises which are external to it: a macro-economic assessment of the wider implications of each scenario, and a Public Participation Process whereby people other than subsistence users can indicate the level of acceptability of each scenario.

DRIFT has been developed in a semi-arid, developing region, where water-supply problems are pressing, and uncertainties about river-linked ecological and social processes high. The use of DRIFT in this context is discussed.

2.3 Introduction

Increasing water demands are degrading river and other aquatic ecosystems, in countries across the world. Nowhere is the problem more urgent than in developing countries in semi-arid climates, where fast-growing populations are reliant on very limited water resources. Many of these countries acknowledge that environmental protection must be a component of their management of aquatic resources, but have limited data and understanding of their systems with which to achieve this.

South Africa began to address this problem in the 1980s. First, aquatic ecosystems were recognised as competing users of water, and later, their status was further enhanced as they became seen as 'the base of the resource', with water needs for their own maintenance. In the continuing competition and negotiations for scarce water, the aquatic scientists were asked to speak on behalf of the ecosystems. The problems faced when embarking on this were not trivial, but appear to be common globally. Few relevant data; a limited understanding of the nature and functioning of the ecosystems; limited funds; and few scientists with relevant skills; were just the most obvious difficulties faced. With a growing economy and about half of South Africa's people with inadequate access to potable water, the managers could not wait until these shortcomings had been overcome. Water supply had to be addressed, and decisions on water resources would be made with, or without, scientific input.

Responding to this, in a major shift in thinking and with the support of government, the nation's water scientists moved to provide advice on water allocations for ecosystem maintenance, based on limited knowledge. This heralded a decade of new working relationships, and growing awareness on all sides of the constraints of water management and the complexities of aquatic systems.

This paper describes an holistic approach to advising on environmental flows for rivers, that was a product of this new endeavour. It developed from earlier holistic methodologies, through several applications in southern Africa. The approach cannot be illustrated through comprehensive coverage of case studies, as the outcomes of the flow assessments are presently the subject of regional or international negotiations. Instead, the methodology is described, with examples of specific activities and outcomes from one flow assessment in Lesotho.

2.4 Environmental flows and their assessments

Environmental flows may be defined as water that is left in a river system, or released into it, for the specific purpose of managing the condition of that ecosystem. During the last five decades, about 100 different approaches have been described for advising on environmental flows, and more than 30 countries have begun to use such assessments in the management of water resources (Tharme 1996; King *et al.* 1999).

There are four main types of flow-assessment approaches: hydrological, hydraulic rating, habitat rating, and holistic (King *et al.* 1999). Those based solely on hydrological data were among the earliest. They are essentially desktop methods that use summary statistics of flow, which may or may not be ecologically relevant, to advise on suitable flows, often for fish habitat. Because of their lack of sensitivity to individual rivers, hydraulic-rating methods were developed which use field measurements to describe channel-discharge relationships. Though providing river-specific data, these failed to indicate the significance of changes in the measured physical conditions for the aquatic biota.

This led to the development of habitat-rating approaches, the best known of which is the Instream Flow Incremental Methodology IFIM) (Reiser *et al.* 1989a and b; Stalnaker *et al.* 1995). IFIM links simulations of local channel hydraulics over a range of discharges with data on the hydraulic conditions in which selected species (usually fish) are most frequently found. The output plot of Weighted Usable Area (WUA) versus discharge indicates how these hydraulic habitats increase or decrease in area with discharge fluctuations, providing a simple negotiation and management tool. IFIM marked a milestone in the development of environmental flow methodologies, and was visionary in its approach. It nevertheless attracted considerable early criticism (reviewed in King & Tharme 1994), which triggered development of the holistic approaches.

Reflecting a growing body of thought, the Building Block Methodology (BBM) in South Africa (King & Louw 1998; King *et al*. 2000a), and the Holistic Approach (Arthington *et al*. 1992; Arthington 1998) and Expert Panel Assessment Method (Swales & Harris 1995) in Australia, were developed in the early 1990s to advise on flows for maintenance of the whole ecosystem. Whether used to inform on how much water should be released into a river, or the limit of abstraction from it, or the restoration of flows, they are based on the same philosophy. This is, that to manage the condition of a river:

- all major abiotic and biotic components constitute the ecosystem to be managed;
- the full spectrum of flows, and their temporal and spatial variability, constitute the flows to be managed.

The holistic approaches are essentially processes that allow aquatic scientists from many disciplines to integrate data and knowledge. Each specialist uses methods of her/his choice to develop an understanding of flow-ecosystem relationships, and then works with the other team members, within the over-arching process of the holistic approach, to reach consensus on environmental flows. The output is a description of a flow regime, in terms of frequencies, timing and duration of different magnitude flows, needed to achieve and maintain a specified river condition.

The BBM triggered a major change in the way specialists collected and analysed data in South Africa, but had two major weaknesses. First, it was essentially prescriptive. A river condition is specified, and then the recommended flow regime to achieve it described. The outputs do not lend themselves to negotiation, because effort is mostly directed to justifying a single flow regime, and information on the implications of not meeting it is not easily accessed. Second, it did not adequately address the impacts of changing rivers on subsistence users. These social impacts are part of the costs of water-resource developments in many developing countries, but are still rarely described (King *et al.* 1999).

DRIFT (Downstream Response to Imposed Flow Transformation), is a new holistic methodology that incorporates features from the earlier ones and addresses these two problems, through the production of biophysical and socio-economic scenarios. Here, the over-arching process is described. Details of the activities undertaken by each specialist are given in the Manual for the BBM (King *et al.* 2000a), which requires the same kinds of data inputs as DRIFT.

2.5 DRIFT within the catchment-planning and management arena

DRIFT was developed in actual water-resource development projects, on the Palmiet River (Brown *et al.* 2000) and Breede River in South Africa, and in the Lesotho Highlands Water Project in Lesotho (Metsi Consultants 2000a). It was further developed in 2001 in a technology-transfer exercise on the Odzi and Pungwe Rivers in Zimbabwe (H. Steward, Mott Macdonald, UK. pers. comm.). It is designed to describe selected potential flow regimes, each linked to the predicted:

- biophysical consequences in terms of condition of the river ecosystem;
- socio-economic consequences for subsistence users of the river, resulting from the changing river condition;
- water yield of the scheme.

Each such array of information is here called a scenario.

Two allied activities should occur in parallel to the DRIFT application but outside it (Figure 2.1). First, an assessment of the wider consequences of each flow scenario should be done to illustrate related macro-economics, such as the loss or gain of irrigated agricultural land, the potential for industrial and urban development and the cost of water to offstream users. Second, a Public Participation Process (PPP) should run parallel to DRIFT throughout its application. Initially, the PPP provides input to DRIFT on river concerns that need to be described in each scenario, such as a recreational fishery, a conservation area, a riverside business or a flood hazard. Following this, a continuing process of information exchange and education should allow interested parties to understand the scenarios developed in DRIFT and to indicate the degree of acceptability of each. All three activities thus produce independent but related information for the decision maker. Only the DRIFT component is addressed here, which focuses on the river ecosystem and subsistence users of its resources. If there are no subsistence users, DRIFT can be applied without the socio-economic module. Other users of the river should be represented through the macro-economic or PPP components.

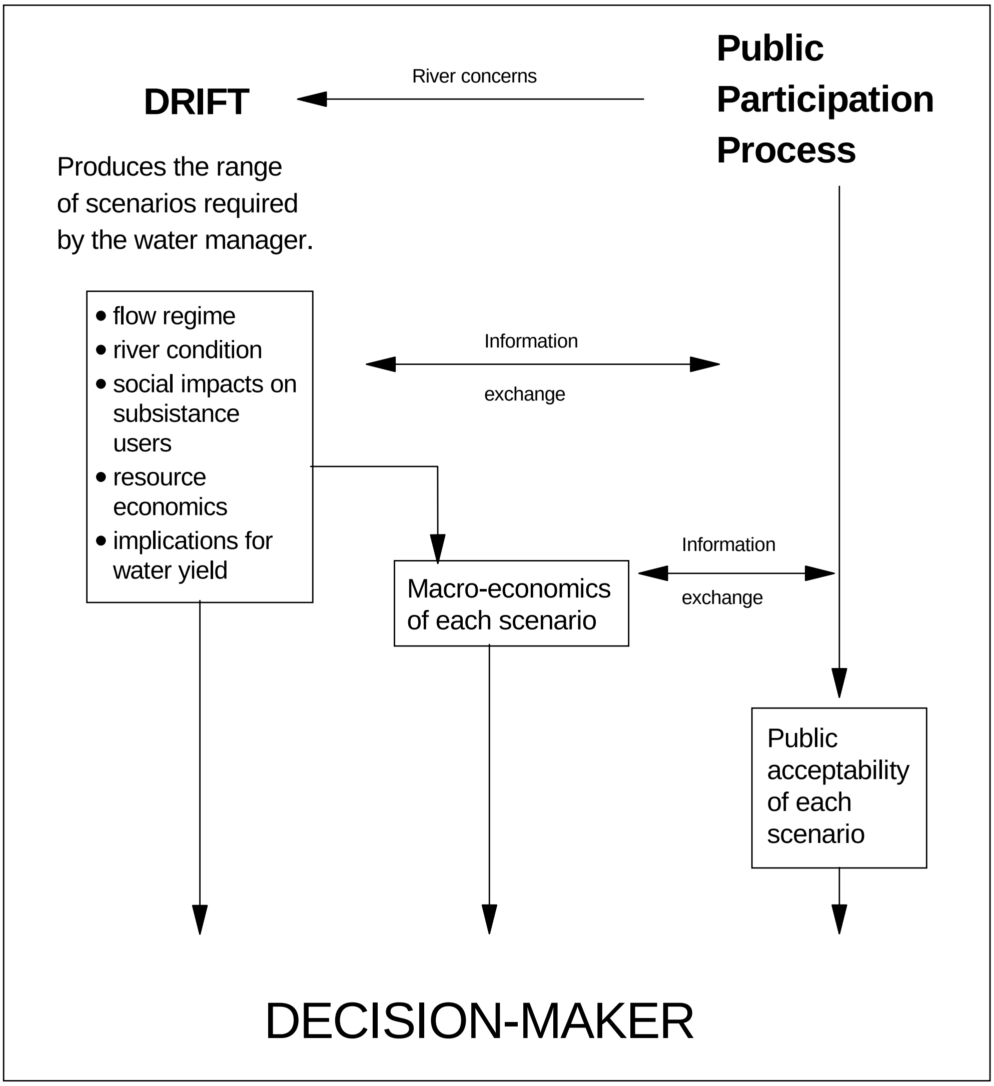

Figure 2.1 The interdependence of DRIFT, a Public Participation Process, and a macro-economic assessment, in a proposed water-resource development.

2.6 Overview of DRIFT

Like other holistic approaches, DRIFT is essentially a data-management tool, allowing data and knowledge to be used to their best advantage in a structured process. Its central rationale is that different parts of the flow regime elicit different responses from the river ecosystem (Table 2.1). Thus, removal of one part of the flow regime will affect the ecosystem differently than removal of another part. Furthermore, it is assumed that:

- it is possible to identify and isolate these different parts of the flow regime within a long-term hydrological data set of daily flows;

- it is possible to describe in isolation the probable biophysical consequences of partial or whole removal of any one of these parts;
- the parts of the flow regime and their linked consequences can be re-combined in various ways, to describe the river condition of any flow regime of interest (the biophysical part of the scenario);
- the social impacts of each river condition can be described (the socio-economic part of the scenario).

Although the same process can be used in the opposite direction to add back flows as part of rehabilitation of a degraded river, in this paper we focus on flow reductions.

Table 2.1 Different kinds of river flow, and their importance to ecosystem functioning

Flow	Importance to ecosystem
Low flows	These are the daily flows that occur outside of high-flow peaks. They define the basic hydrological nature of the river: its dry and wet seasons, and degree of perenniality. The different magnitudes of low-flow in the dry and wet seasons create more or less wetted habitat and different hydraulic and water-quality conditions, which directly influence the balance of species at any time of the year.
Small floods	Small floods are ecologically important in semi-arid areas in the dry season. They stimulate spawning in fish, flush out poor-quality water, mobilise and sort gravels and cobbles thereby enhancing physical heterogeneity of the riverbed, and contribute to flow variability. They re-set a wide spectrum of conditions in the river, triggering and synchronising activities as varied as upstream migrations of fish and germination of riparian seedlings.
Large floods	Large floods trigger many of the same responses as do the small ones, but additionally provide scouring flows that influence the form of the channel. They mobilise coarse sediments, and deposit silt, nutrients, eggs and seeds on floodplains. They inundate backwaters and secondary channels, and trigger bursts of growth in many species. They re-charge soil moisture levels in the banks, inundate floodplains, and scour estuaries thereby maintaining links with the sea.
Flow variability	Fluctuating discharges constantly change conditions through each day and season, creating mosaics of areas inundated and exposed for different lengths of time. The resulting physical heterogeneity determines the local distribution of species: higher physical diversity enhances biodiversity.

Based on the above assumptions, DRIFT consists of four main modules (Figure 2.2). The first, or biophysical module, is used to describe the present nature and functioning of the ecosystem, and to develop predictive capacity of how these will change under a range of different flow manipulations. A database of predicted flow-related changes is created. The second, or sociological module, is used to identify subsistence users at risk from flow manipulations (the Population at Risk: PAR), and to quantify their links with the river. In the third module, the outputs from the first two are brought together to produce the biophysical and subsistence scenarios. The fourth module addresses the costs of mitigation and compensation.

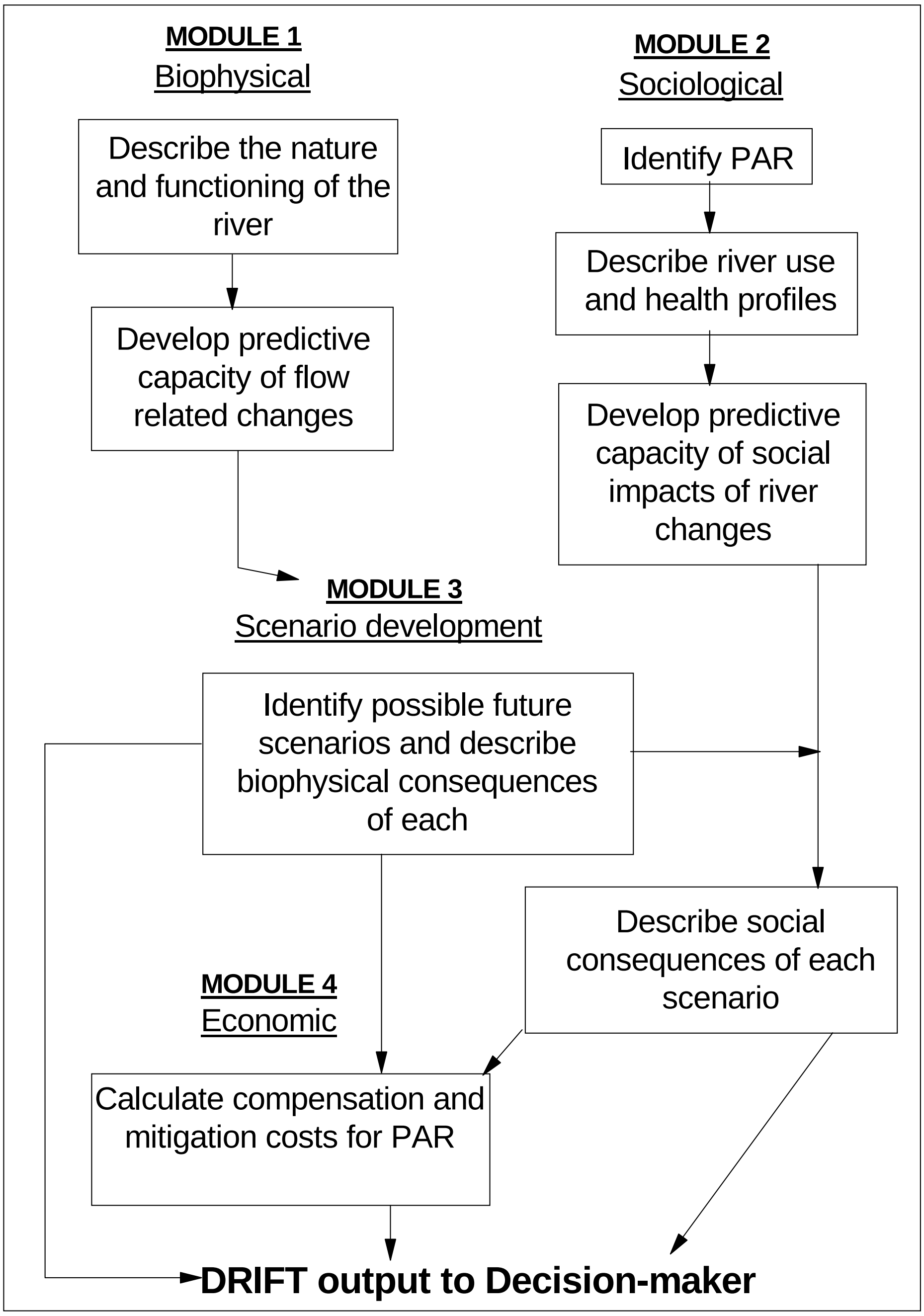

Figure 2.2 The four modules of DRIFT.

Module 1 - biophysical

The biophysical specialists typically involved in a DRIFT application are: hydrologist, hydraulic modeller, water chemist, fluvial geomorphologist and/or sedimentologist, botanist (riparian and instream), ichthyologist, invertebrate zoologist and, sometimes, specialists dealing with, *inter alia*, aquatic parasites, algae, herpetofauna, aquatic mammals and water birds. The hydrologist and hydraulic modeller provide information on the river that the other specialists use to develop their predictions of change. A summary of the main activities follows, which are detailed in King *et al.* (2000a).

Representative sites

After the study area has been defined, a series of initial assessments are made of all included river reaches to guide the choice of representative sites. Existing or easily acquired data are used to define longitudinal zones that differ in terms of channel morphology, water chemistry and, temperature; and biological zones for fish, invertebrates and riparian vegetation. Based on these results, representative sites are chosen, and the length of river that each represents delineated. Sites are sought with the highest proportion of natural features, because these provide good clues to flow-ecosystem relationships. Compromises may have to be made between specialists, as the number and location of study sites may be restricted by budgets, time constraints or access points to the river.

Background hydrology

An underlying philosophy of DRIFT is that most river scientists take as their starting point in understanding any river, its nature and condition at the time of their studies. Their predictions of flow-related change describe how the river will change from present, although they may use as background any information on past characteristics of it and similar rivers. Therefore, DRIFT takes as its starting point an analysis of the present flow regime of the river, and of how and when that has changed in the past.

Long-term (> 30 y) present-day daily flow data are first simulated for each study site. These are analysed to characterise present flows, in terms of the parts of the flow regime recognised in Table 2.1, with every day's average flow appearing once in the data sets (i.e. no days unallocated or allocated twice).

- *The low flows:* the daily flows between high-flow peaks are divided into data sets for different seasons, usually:
    - wet-season low flows;
    - dry-season low flows.
- *The high flows:* the peak events of higher flow are allocated to one of the following:
    - four size classes of intra-annual floods;
    - floods with a return period of up to 2, 5, 10 and 20 years.

Low flows are distinguished from high flows using one of two criteria: the rate of change of the slope of the daily hydrograph, or the discharge at which selected features of the channel become inundated. The four classes of intra-annual floods are delineated by simple halving of magnitudes from the 1:2-year flood, as halving the magnitude of an event results, in general terms, in a significant change in the sediment-moving power of the flood (A. Rooseboom, Chair of Sedimentation Committee, ICOLD. pers. comm.). Alternatively or additionally, the discharges at which relevant channel features are inundated or exposed are used.

If a different past flow regime might still be responsible for elements of the present character of the river, a similar simulation and analysis of that regime is done, and both are considered in parallel in the following steps.

The result of the analysis, based on a long-term data set that covers wet and dry years, is a summary of the *ranges* of low flows within each chosen season, and the *average number per annum* of high-flow events (Table 2.2). Flow duration curves (FDCs) derived from the low-flow data sets indicate the variability of the low flows and how often any discharge is met or exceeded (Figure 2.3).

Table 2.2 Analysis of the present flow regime at a study site in Lesotho (Metsi Consultants 2000b). Dry season: June to November. Wet season: December to May.

Flow component	**Discharge ($m^3 s^{-1}$)**	**Average number of events per year**
Dry season low flows	0.1 – 16.0	
Wet season low flows	0.1 – 50.0	
Intra-annual flood size class I	16 – 48	6
Intra-annual flood size class II	49 – 95	3
Intra-annual flood size class III	96 – 190	3
Intra-annual flood size class IV	191 – 379	2
1:2 year flood	380	
1:5 year flood	530	
1:10 year flood	665	
1:20 year flood	870	

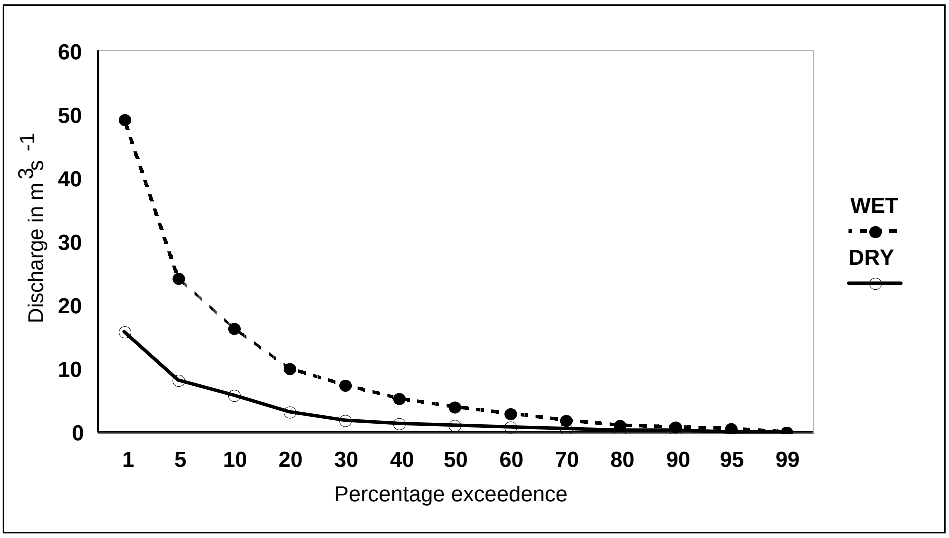

Figure 2.3 Flow duration curves of the wet-season and dry-season low-flow data sets from Table 2.2.

Linking the flow regime to local hydraulic conditions

Conversion of the summary hydrological statistics to information on local hydraulic conditions is the vital link that allows river scientists to understand why river features and species occur where they do. Several (3-7) cross-sections across the complete macro-channel, selected jointly by the scientists and hydraulic modeller, are surveyed at each site, and stage-discharge data recorded over a range of flows. These are used to calibrate a hydraulic model, which is in turn used to derive statistics of depths, velocities and other relevant parameters for each cross-section, at any discharge within a named range.

Graphics of each cross-section are marked to show the extent of each vertical zone of riparian vegetation, as well as any other features of interest, such as riffles, secondary channels, sand, or aquatic vegetation (Figure 2.4). The range of inundated areas in the two low-flow seasons, and the levels reached by each size class of flood, are also shown. These graphics, together with the hydraulic modelling outputs of velocities and depths, the low-flow FDCs, and data on the frequency and timing of different size classes of floods, allow the specialists to develop an understanding of the links between flow and the features or species of interest to them. For example, it could be shown from the FDCs that a vegetation zone situated just above the water line is exposed for about 70% of the dry season outside of any floods, but inundated for 90% of the wet season. Knowing this enables botanists to develop a prediction of the location and extent of this zone under a new flow regime.

Further aids to the development of predictive capacity are habitat maps of the sites, on which major hydraulic habitats are delineated, with data on their hydraulic characteristics over a range of flows (Figures 2.5 and 2.6). Using these, for example, the ichthyologist could link a fish species to areas of high or low velocities within a site, and be able to predict its different distribution under a different flow regime.

Developing predictive capacity

Each biophysical specialist chooses her/his own component-specific methods to derive the kinds of flow-related links described above. PHABSIM, for instance, could be used to establish links between WUA and discharge for selected fish species. Plant and animal ecologists could use such multivariate-analysis packages as PRIMER (Clarke & Warwick 1994) and CANOCO (Ter Braak 1987) to establish flow-species relationships and be able to use strong inference in their predictions of likely change.

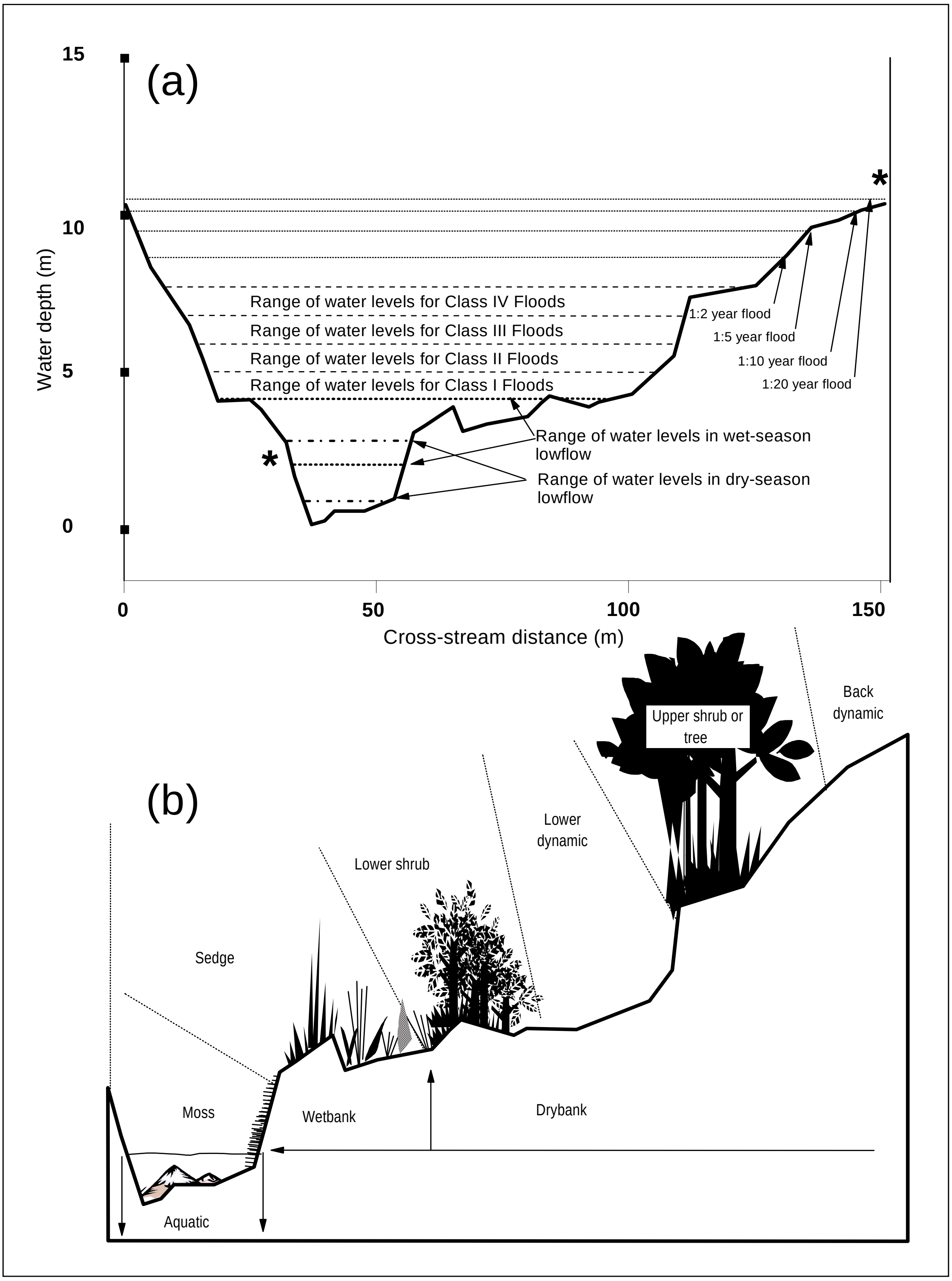

Figure 2.4 Linkage of hydrological data to river cross-sections: a) discharge ranges for all flow components and corresponding water depths; b) expanded detail of one bank (* to *), with zones of riparian vegetation and other features which can be linked to different water levels.

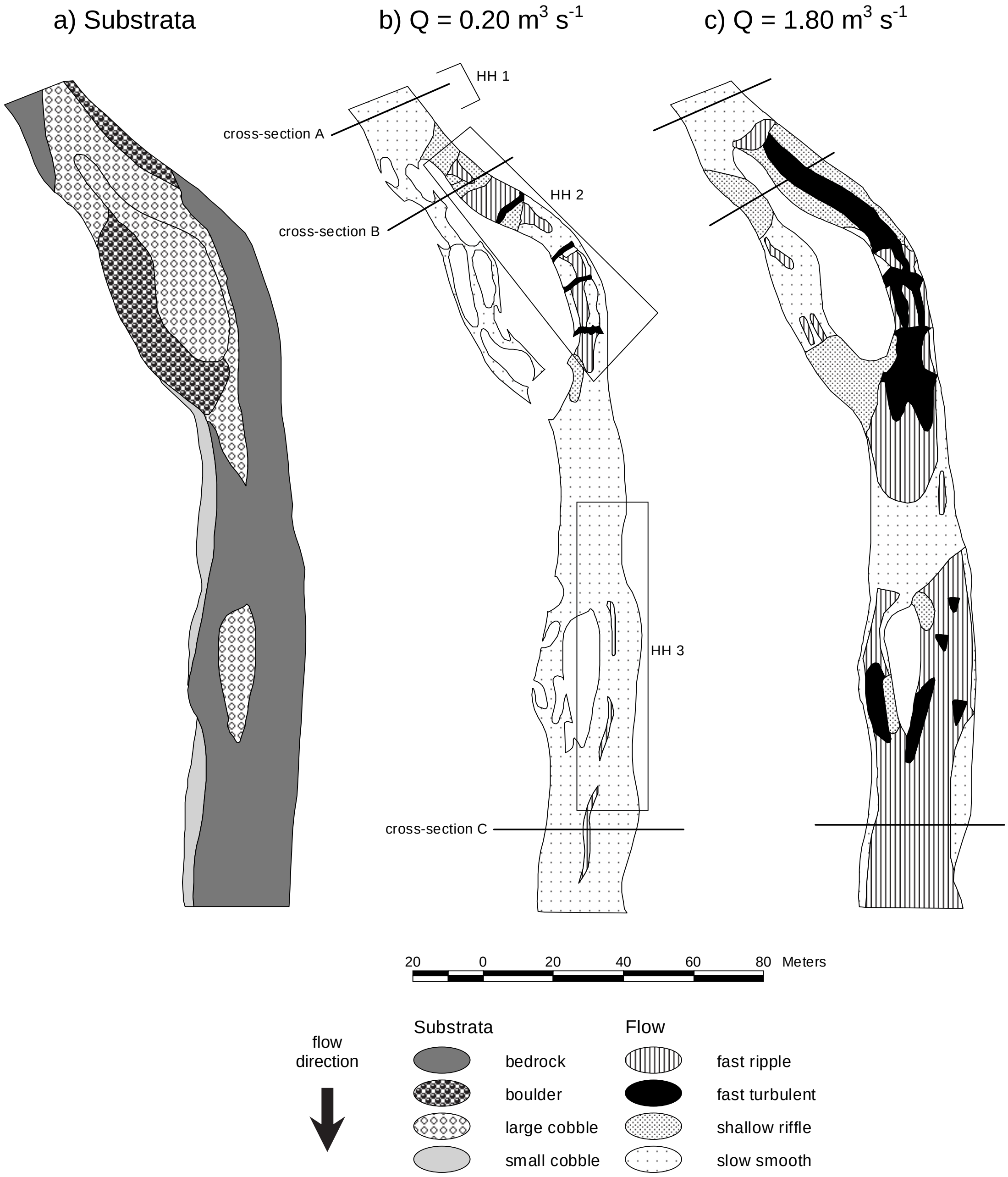

Figure 2.5 Habitat maps and delineation of different hydraulic habitats in a study site in Lesotho: a) substratum map; b and c) flow-type maps, with three distinctly different hydraulic habitats (HH) delineated (Metsi 2000c and d). Definitions of flow types simplified from King and Schael (in press). HHs developed from an original idea by Angela Arthington, Johan Rall and Mark Kennard Metsi Consultants, 2000d).

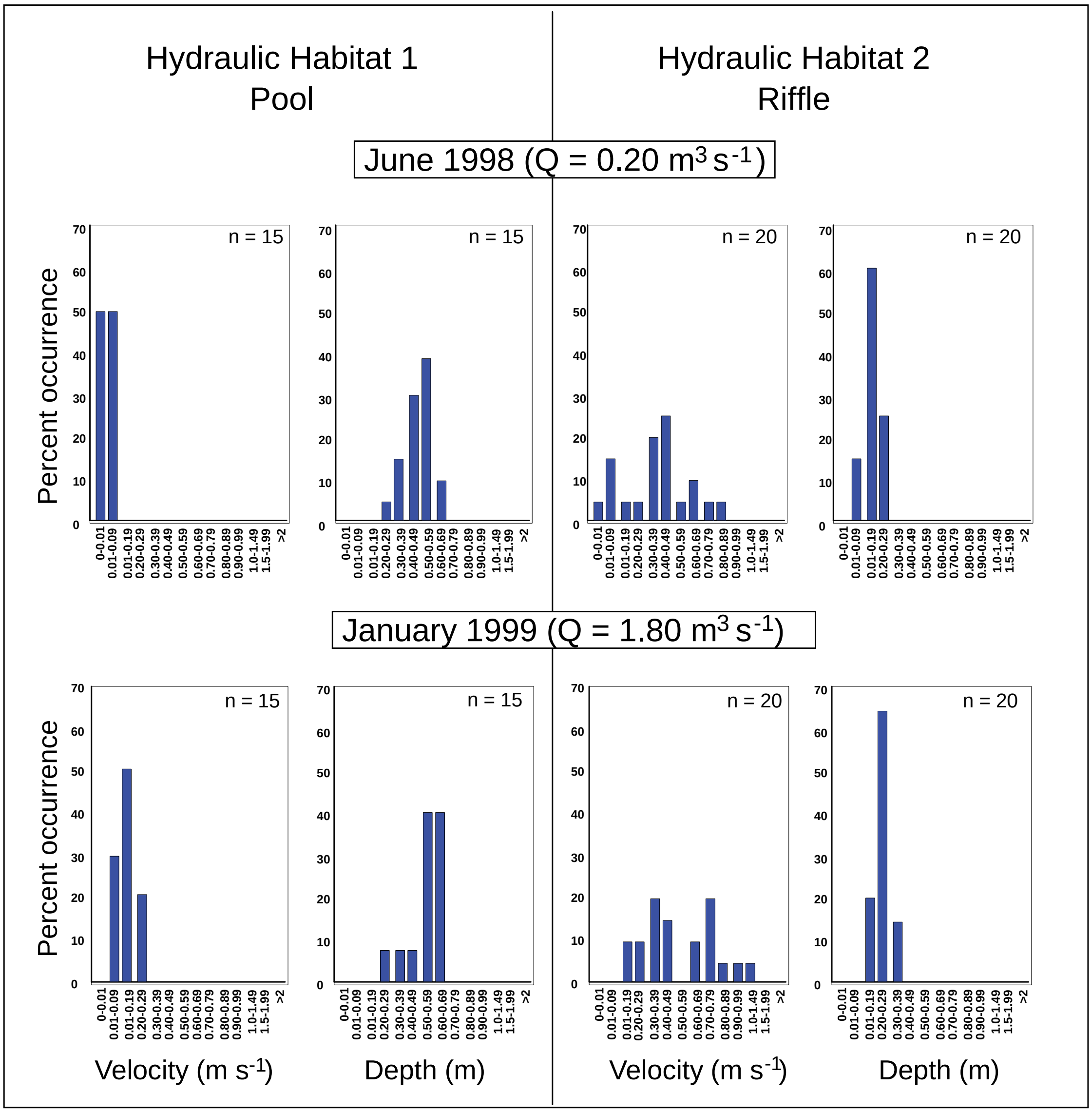

Figure 2.6 Discharge-related changes in velocity and depth for HH1 (pool) and HH2 (riffle) in Figure 2.5. Q = discharge.

The goal for each specialist is to be in a position to predict how a specified set of flow reductions (or additions) would change their component of the ecosystem. The changes are quantified to the extent possible (see section on Severity Ratings). Obviously, the greater the investment in river studies to achieve predictive capacity, the higher the confidence in the predictions.

Reducing flows and describing consequences

With the data-analysis phase complete, a series of flow-reduction levels are decided upon, and the specialists use their data to predict the consequences. This is best done together in a workshop environment, so that all can understand the predicted changes. Typically, for each flow reduction, the geomorphologists first describe anticipated changes to the physical environment, followed by the aquatic chemists outlining chemical and thermal changes, and then the vegetation specialists describe shifts in aquatic and riparian plant communities. At this stage, the predicted changes to the environment of the fauna have been described, allowing the fish and invertebrate (and any other faunal) specialists to record their predictions.

Flow reductions consist of reducing the *range* of low flows and the *number* of flood events**.** Thus (Table 2.3), at the study site in Lesotho used in Table 2.2, the top end of the low-flow range for the dry season at the site in Table 2.2 was initially reduced from 16.0 to 9.0 $m^3 s^{-1}$ and, *assuming that all the other flow components would remain unchanged*, the consequences of this single reduction described. The top end was then further reduced through three more levels, reducing both range and variability of the remaining flow. At each step the consequences were recorded. This was repeated for the wet-season low-flow range. In both cases, reduction level 1 was to "Minimum Change" level – a reduction that the specialists jointly identified as having a minimal impact on present river condition.

Table 2.3 Flow reduction levels at a study site in Lesotho

Flow component	**Natural Q ($m^3 s^{-1}$)**	**Number per year**	**Reduction level 1 (Minimum Change)**	**Reduction level 2**	**Reduction level 3**	**Reduction level 4**
Dry season low flows	0.1 – 16.0		0.1 – 9.0	0.1-3.0	0.1-1.0	0.1-0.5
Wet season low flows	0.1 – 50.0		0.1 – 25.0	0.1-10.0	0.1 – 5.0	0.1 – 1.0
Within-year flood I	16-48	6	3	1	0	-
Within-year flood II	48-95	3	2	1	0	-
Within-year flood III	95-190	3	2	1	0	-
Within-year flood IV	190-380	2	1	0	-	-
1:2 year flood	380	Function and consequence of loss				
1:5 year flood	530	Function and consequence of loss				
1:10 year flood	665	Function and consequence of loss				
1:20 year flood	870	Function and consequence of loss				

The consequences were then recorded of up to four levels of reduction in the number of each size class of intra-annual flood (Table 2.3). For each class of floods, the number that could be removed with Minimum Change was identified. Finally, the significance for river functioning of the four larger size classes of floods, and the consequences of their being lost, were recorded.

Using generic lists to predict the consequences of flow reductions

When recording the consequences, each specialist works with a generic list that can consist of any number of items, but usually four to less than twenty, compiled before the flow-reduction exercise started (Table 2.4). For each flow reduction at each study site, the affect on every item on the lists is described. The list items may comprise processes, habitats, communities or individual species, and are chosen based on their known susceptibility to flow changes, their role as key species or features, or their relevance to subsistence users. In Lesotho, about 130 items were included in the various lists and, with all eight study sites and reduction levels considered, more than 20,000 consequences recorded. These were entered into a custom-built database.

Using severity ratings to quantify the consequences of flow change

Into the foreseeable future, predictions of river change will be based on limited knowledge. Most river scientists, particularly when using sparse data, are thus reluctant to quantify predictions: it is relatively easy to predict the nature and direction of ecosystem change, but more difficult to predict its timing and intensity. To calculate the socio-economic implications of loss of resources to subsistence users, for use in compensation and mitigation programmes, it is nevertheless necessary to quantify these predictions as accurately as possible.

Table 2.4 Examples of entries in generic lists for the Lesotho study

Discipline	**Generic list entry**	**Description of the links to flow and social relevance**
Geomorphology	Deposition of colloidal material	Minimum velocity for maintenance of movement of colloidal material in main channel = $0.05\ m\ s^{-1}$.
		Muddy areas are linked to loss of cobble habitat, increased algal growth, bogging of livestock, and gastric illnesses.
Water quality	Nutrient levels	Nutrient levels in pools increase under low flow conditions. Water in pools flushed by > Class II floods.
		High nutrients encourage algal growth, which is linked to increased incidence of diarrhoea in people and livestock, and loss of cobble habitat.
Vegetation	*Chenopodium album*	Found mostly in the wetbank vegetation zone, the width of which is reduced by a reduction in the volume and variability of lowflows and in the number of Class I floods. Abundance is affected by narrowing the zone.
		Important source of firewood. Also used as a medicine.
Fish	Maluti Minnow	Inhabits quiet, shallow waters in rocky reaches with high water quality
		IUCN Red Data Book rare species. Restricted to the Highlands of Lesotho. Threatened with extinction.
Invertebrates	*Simulium nigritarse*	Filter feeder in slow, eutrophic water.
		Blood-sucking pest of poultry.

DRIFT addresses this uncertainty using severity ratings. River scientists are usually willing to predict the change in abundance of each item on their generic list on a six-point scale that spans no change to critically-severe change (Table 2.5). This scale already accommodates uncertainty, as each rating encompasses a range. Greater uncertainty can be expressed through providing a range of severity ratings (i.e. a range of ranges) for any one predicted change.

For the financial calculations, the severity ratings are converted to percentages of resources lost, or increased health risks, using appropriate conversion factors. The conversions have to be able to show that a critically severe loss equates to local extinction whilst a critically severe gain equates to proliferation to pest proportions. One possible route uses cut-points at 20% intervals for losses between 0% and 100% (Table 2.5). The analogous route used for gains employs a multiplying factor exceeding one (‘r’), such that a gain of 25%, for instance, is equivalent to r = 1.25. The inverse of ‘r’ then lies between zero (which represents an increase to pest proportions when r = ∞) and one (no change). The same linear divisions on the inverse scale can then be used for gains and losses. For example, with a 25% increase in abundance, r = 1.25 and 1/r = 0.8, which is the outer limit of the 'negligible' gain category (Table 2.5) (Prof. L. G. Underhill, Dept of Statistical Sciences, University of Cape Town).

A consequence entry

Each consequence described by the specialists and entered into the database links a site with a flow-reduction level, a discipline, an item from the generic list for that discipline, and the predicted direction and severity of change (Table 2.6). To aid interpretation of impacts, the ecological and social significances of the generic-list item are also entered.

Table 2.5 Severity ratings for predictions of change in abundances, and conversion to percentages

Severity rating	**Severity of change**	**Equivalent loss** (abundance retained)	**Equivalent gain**
0	None	no change	no change
1	Negligible	80-100% retained	1-25% gain
2	Low	60-79% retained	26-67% gain
3	Moderate	40-59% retained	68-250% gain
4	Severe	20-39% retained	251-500% gain
5	Critically severe	0-19% retained; includes local extinction	501% gain to ∞: up to pest proportions

Table 2.6 One consequence entry in the database

Sequence	Category	Information
1	Site	2
2	Flow reduction level	Reduction level 4 of dry-season low flows
3	Specialist	Invertebrates
4	Generic list entry	*Simulium nigritarse*
5	Direction of change in abundance	Increase
6	Severity of change	Rating 5: critically severe
7	Conversion to percentage	500% gain or more – probable pest proportions
8	Ecological significance	Filter feeder in slow, eutrophic water
9	Social significance	Blood-sucking pest of poultry

With the database populated, the biophysical module is complete and ready for Module 3.

Module 2 - sociological

Specialists involved in this module (Figure 2.2) can include sociologists, anthropologists, medical doctors and other public health specialists, veterinarians (livestock); experts on community water supply, economists and resource economists. Again, each chooses her/his own methods, in order to understand the relationships between the river and the PAR, and to develop predictive capacity of the consequences of river changes. The main tasks are: to describe the PAR; quantify its use of river resources; and understand the links between the river and human and livestock health.

Describing the Population at Risk

The PAR is recognised as those people who live along the river and use its resources for subsistence. The first step in describing their links with the river is to delineate the width and length of the river corridor within which they live. The corridor could differ in width along its length as people make more or less use of the river. The main criteria dictating its dimensions may be the distance people are prepared to walk to use the river, ease of access to the river bank and channel, and availability of alternate resources. With the corridor delineated, all parts of it are allocated to and represented by one of the biophysical study sites. The number of people in each such part is ascertained, perhaps through government census data or aerial photographs.

Quantifying resource use

The PAR's use of river resources is then quantified (Table 2.7, Figure 2.7), and their sources and use of potable water established. The present economic value of these resources is calculated.

Table 2.7 Examples of river resources used by the PAR in the Lesotho study, and their economic values (Metsi Consultants 2000e)

Fish are caught by 5,098 households, which catch an annual average of 17.5 kg of smallmouth yellowfish, 2.2 kg of rock catfish, and 3.0 kg of rainbow trout. The approximate market value of fish is 10 Maloti per kg.
Wild vegetables are harvested by 13,911 households, which harvest on average 148 plastic bags per year with a mean market value of 2.08 Maloti per plastic bag.
Casual drinking is done by 17,354 households, who drink from the river on average 16.1 times per month in summer and 8.9 times per month in winter.
Crops in the riparian zone are owned by 4,131 households, which produce a mean annual harvest of 155 kgs.

Describing river-related health risks

Health professionals familiar with the area first identify all existing and potential health threats to the PAR and their livestock (Figure 2.7). The present occurrence of these threats is established by compiling health profiles of the people and livestock. The best sources for such data may be government public-health and veterinary programmes. Water-related illnesses listed in the health profiles are identified, and the degree to which the river presently contributes to such illness is established via two routes. First, current use patterns of the river are recorded. Close liaison between the health and sociological teams allows the necessary data on use patterns to be gleaned during the social studies. Second, through liaison with the biophysical team, the causes of the illnesses are identified and, where appropriate, incorporated in the biophysical study programme. For example, diarrhoea may presently occur in the PAR, being most common among people who drink from the river, and this may be attributed to a stomach parasite such as *Giardia*, which is then included in the microbiological studies.

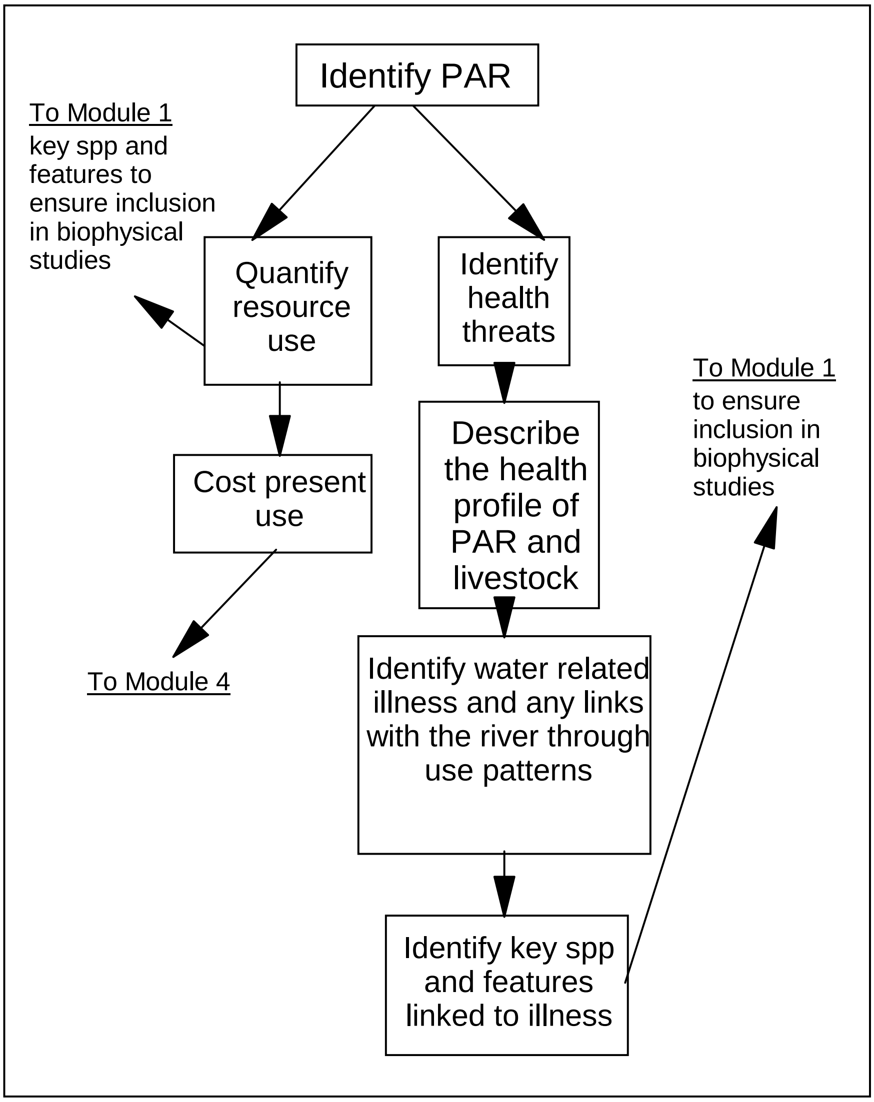

Figure 2.7 Detail of Module 2: the Sociological Module

With the above data sets in place, the present relationships between the river and the PAR have been described, and an understanding developed, albeit perhaps not quantitatively, of how river changes could impact the PAR. To ensure the best possible outputs from Module 2, strong links need to be forged between the biophysical and socio-economic teams throughout the study but particularly at the following key points:

- early in the project, key river species or features, seen as valuable resources used by the Population at Risk (PAR) or as pests, are factored into the biophysical studies,
- health links with the river are identified at an early stage, so that key organisms are factored into the biophysical studies;
- the socio-economic team attends all meetings of the biophysical team, so that they can develop an understanding of the descriptions of river change;

- the socio-economic team ensures that all items of social concern are represented in the generic lists, and explains their significance, so that the ways in which these change can be described in a relevant way for every scenario.

This Module is then complete and ready for Module 3.

Module 3 – scenario development

The scenarios provide a series of possible future flow regimes, together with their consequences. Within each scenario, the biophysical descriptions of river change are linked to the socio-economic impacts on the PAR and to the yield of water after the planned flow manipulation. In DRIFT, scenario development begins with identification of the range and kinds of scenarios that the decision-maker would like to consider. In theory, any number of scenarios can be compiled from the database, although experience has shown that with our present understanding of river functioning, usually four to five is the most that can be perceived as distinctly different.

The biophysical component of the scenarios

Initially, for each selected scenario, the future flow of each site is simulated, and analysed to show how each flow component would differ from present. For instance, under the Minimum Change scenario, future flows at the Lesotho site described in Table 2.2, with a large dam in place, would have the following characteristics (Table 2.8).

- The top end of the range of dry-season low-flows is reduced from 16.0 to 9.0 $m^3 s^{-1}$, and the wet-season low flows from 50.0 to 25.0 $m^3 s^{-1}$.
- Three of the six Class I floods are lost, one of the three Class II, one of the three Class III, and one of the two Class IV floods.
- All larger floods should still occur, except those with around a five-year return period.
- Sixty-six percent of the natural flow remains in the river.

Table 2.8 Flow reduction values for the Lesotho site. MAR = mean annual runoff. Env flow = environmental flow released downstream for river maintenance.

Flow component	**Natural Q $m^3 s^{-1}$**	**Number per year**	**Scenario 1 (Minimum Change)**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Dry season low flows	0.1 – 16.0		0.1 – 9.0	0.1 – 1.9	0.1 – 1.9	0.5
Wet season low flows	0.1 – 50.0		0.1 – 25.0	0.1 – 1.2	0.1 – 1.2	0.5
Class I flood	16 – 48	6	3	3	2	1
Class II floodI	48 – 95	3	2	1	0.5	0
Class III flood	95 – 190	3	2	2	0.5	0
Class IV flood	190 – 380	2	1	0	0	0
1:2 year flood	380		P	A	A	A
1:5 year flood	530		A	A	A	A
1:10 year flood	665		P	P	A	A
1:20 year flood	870		P	P	P	P
% MAR as env.flow			**66**	**33**	**18**	**4**

Scenario 4, designed to maximise water storage, provided the opposite extreme (Table 2.8).

- Low-flows remain at a steady year-round dam release of 0.5 $m^3 s^{-1}$.
- All small to medium floods are harvested by the dam, but on average one Class I flood is generated per year by the downstream catchment.
- All large floods up to that with a 20-year return period are harvested by the dam.
- Four percent of the natural MAR remains in the river.

Scenarios 2 and 3 provided interim conditions (Table 2.8), with 33% and 18% of MAR remaining in the river.

Knowing the nature of future flows, the database can be queried for the predicted consequences. For each site and each scenario, each part of the flow regime (i.e. each row in Table 2.8) is matched with its closest reduction level in the database. All the relevant consequences are extracted and synthesised, and synergistic affects taken into account. This step has to be done by one or more experienced river ecologists, as sometimes decisions will have to be made on the overall impact of a number of linked but slightly different consequences. The resulting river changes can be presented at several levels of resolution, from detailed quantitative descriptions to summary statistics, or a simple summary map of the river system on which the different severities of change are colour-coded. A description, for instance, could include: *In reach X, there will be a critically severe (80-100%) decline in numbers of fish species A and B, and species A will probably become locally extinct. All other fish, except species C, will show a severe (60-80%) decline in numbers, whilst species C, which is a bottom feeder, will show a no to negligible (0-25%) increase in numbers.*

The sociological component of the scenarios

The sociological team translates the descriptions of river change into impacts facing the PAR, using the understanding developed in Module 2. The impacts fall into two categories: changes in resources and changes in health profiles.

The impact of changing resources can be quantified because the biophysical scenarios describe the predicted loss or gain in abundance of species or features, and the monetary implications of this are known (Table 2.7). This information moves directly through to Module 4.

The impact of changing health profiles and of overall change in the quality of life is more difficult to quantify. Where appropriate methods exist they should be employed, but in most cases expert opinion may have to be used. A number of considerations aid conclusions on the probable level of impact (Table 2.9):

- different river uses are linked to different illnesses;
- different river changes will affect health in different ways;
- frequency of river use heightens the chance of water-related illnesses;
- even with a high frequency of river use, a known health threat can be mild and thus of low impact.

Table 2.9. Examples of health risks related to river change (Metsi Consultants 2000e) and hypothetical levels of health consequences

Nature of river use	Biophysical change	Health risk	Frequency of river use	Relevance for public health
Drinking, washing	Increase in colloidal material leads to an increase in the protozoan parasite *Giardia lamblia*	Increased diarrhoeal disease.	High	High
			Low	Moderate
Grazing and housing near river	Increase in Simuliidae (Blackflies) leads to increased pestering of PAR and livestock and higher levels of disease transmission.	Faecal-oral route of infection. Decreased livestock production.	High	Low
Swimming, baptizing washing	Increase in host snail *Bulinus* leads to increased risk of encountering *Schistosomiasis haematobium*	Increase in incidence of Bilharzia	High	High
Fishing	Decrease in fish leads to loss of important protein source	Nutritional deficiencies	High	High
Harvesting	Decrease in wild vegetables and herbs leads to loss of nutritional supplements and medicines.	Nutritional deficiencies and untreated illnesses.	Low	Low

The outcome of the health assessment is a description, probably qualitative rather than quantitative, of the social implications of each scenario. This information moves through to Module 4.

Module 4 - economic

A taxonomy of values (Figure 2.8) illustrates the range of values that can be attributed to an ecosystem such as river. Moving from left to right across the graphic, the values become progressively less easy to quantify. Those to the left, being more amenable to quantification, can be included in the environmental-flow study, whilst those to the right are probably best included in the PPP (Figure 2.1). In the Lesotho study, only the direct resource-use values to the left were included in the flows study, to produce the costs of mitigation and compensation for each scenario.

We define mitigation here as changes to project design, operation or management to reduce impacts. Compensation is relevant where mitigation does not entirely reduce the impacts. We define compensation as the provision of cash, goods or services to the PAR, to replace lost resources or impeded activities. Mitigation is inherent in the scenarios described. For instance, Scenario 1 in Table 2.10 represents a high level of mitigation, but with a low return in terms of harvested water. Scenario 4 represents a very low level of mitigation, with a high return in terms of harvested water. As yield (and income) from the scheme increases, so do the ecological and social impacts and the cost of compensation (Table 2.10), particularly in the reaches close to the dam.

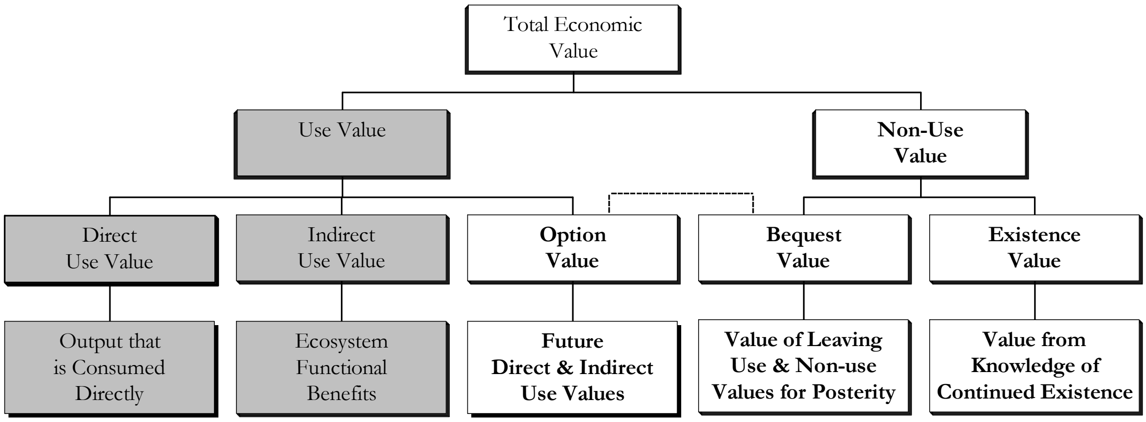

Figure 2.8 Taxonomy of economic values (Metsi Consultants 2000f). The shaded items were addressed in the Lesotho study.

Table 2.10 summarises the DRIFT outputs and outlines the trade-offs that should be considered by decision-makers, along with the macro-economic assessment and the PPP findings. During negotiations, alternative scenarios, or adaptations to the original ones, can be derived from the database as required.

Table 2.10 Summary of the trade-offs to be considered by the decision-maker for likely impacts of proposed dams in Lesotho on the downstream environments. Each box has comprehensive supporting data. Dam yield is given as a percentage of natural MAR.

Scenario	Proximity to dam wall	Change in river condition	Social impact	Compensation required	Yield of water
1 High mitigation	proximal	Low-moderate	Low	Low	34%
	distant	Negligible	Negligible	Negligible	
2	proximal	Severe	Moderate	Medium	67%
	distant	Low	Low	Low	
3	proximal	Severe	Severe	High	82%
	distant	Moderate	Moderate	Medium	
4 Low mitigation	proximal	Critically severe	Critically severe	Very high	96%
	distant	Severe	Severe	High	

2.7 Further development of DRIFT

There are two areas in which the quality of DRIFT applications can be enhanced: through better information on flow-ecosystem links, and through improvement of the methodology itself. Within the disciplines, better understanding of flow-ecosystem links is growing (e.g. Birkhead *et al.* 1997; Jewitt *et al.* 1998; Tharme & King 1998; Rowntree & Wadeson 1999; Breen *et al.* 2000; Jewitt & Görgens 2000; King & Schael 2001), and this is not addressed here. Within the methodology, development is focusing on DRIFT-HYDRO – the hydrological software for summary statistics, DRIFT-SOLVER – the software package for building scenarios; and methods for quantifying the impacts on subsistence users.

The primary area of concern remains the level of uncertainty in any scientific study of this nature. This is discussed below.

2.8 Conclusions

Major factors in any water-resource development or operation are likely to be poor understanding of the river ecosystem, and uncertainty on how it will respond to disturbance. The uncertainty is probably greatest in semi-arid regions, where hydrological unpredictability is high, and in developing countries, where data may be sparse. In these, or any, situation, the choice for aquatic scientists lies somewhere along the spectrum of giving no advice until more data are available, to advising with present, limited knowledge. In South Africa, a four-part strategy is being adopted.

- A comprehensive national programme of research on environmental flows (increasing the knowledge base).
- Use of best available knowledge from these programmes, together with directed short-term research, to answer management questions on flow (moving ahead with limited knowledge).
- Monitoring the outcomes of the management actions (learning by doing).
- Adjustment of management plans, where indicated by monitoring results (strategic adaptive management).

DRIFT is one tool in this strategy. It marks an advance in environmental flow assessments, through its use of scenarios, and linkage of the natural and subsistence components of river ecosystems. It provides decision-makers with information that usually remains unconsidered in water-resource developments, on potential human and ecosystem costs. The scenarios provide a number of future options on how the river could change with flow changes, and how this would impact overall environmental condition and subsistence users. These scenarios can be used as the basis of negotiations between countries, regions or different interest groups. Additional inputs to the negotiations could be the macro-economic implications of each scenario, and the acceptability of each to the wider community of interested parties. These two additions are external to DRIFT. The outcome of the negotiations is usually selection of one scenario as 'the desired state' for the river, with the flow regime described by that scenario becoming 'the environmental flow'. The detailed descriptions held within that scenario, of predicted impacts to both ecosystem and subsistence users, provide the indicators for a monitoring programme that will measure goal attainment.

Application of DRIFT and its predecessors has highlighted knowledge gaps, which have become the subject of research projects. Meanwhile DRIFT, working with present knowledge levels, addresses uncertainties in a number of ways.

- Highly experienced river scientists are used, who have a good understanding of the rivers of their region.
- The scientists reach consensus on the predicted ecological and subsistence outcomes of any flow manipulation. In law, consensus by an experienced group is a greater strength than the advice of a single specialist (C. Palmer. Institute for Water Research, Rhodes University. pers. comm.).
- Quality control of data takes place in standard ways, and also through matching of data sets. As an example, different sized floods, with different return frequencies, should each reach up the banks to a specific zone of riparian vegetation (Figure 2.4) (hydrological, surveying, hydraulic and botanical data sets in agreement).
- The flow assessment is structured, fully recorded and transparent, allowing understanding of the derivation of the scenarios and the levels of uncertainty.
- Severity ratings allow a scenario to be illustrated as a 'risk envelope' that defines the range of the predicted changes. The wider the envelope, the greater the uncertainty in the prediction.
- Monitoring and adaptive management strategies allow learning to continue, predictions to be validated and goal attainment re-assessed.

The presentation of several scenarios allows the decision-maker to assess not only the traditional engineering and economic implications of a water development, but also the ecological and subsistence ones. Selection of one scenario is then best done through a structured, transparent decision-making process that facilitates negotiations and trade-offs.

Increasingly, the aim of such decisions is to ensure sustainable use of aquatic resources. This aim may not be met if moves by scientists to advise with limited knowledge are not counterbalanced by a management agreement to support knowledge development. Without this, there is the danger that the early advice will become all that is sought and used. Learning may then be limited and wrong thinking could persist. A commitment to sustainable use requires a commitment to: implement the selected flow regime; monitor the outcome in a way that will unambiguously indicate if it is achieving its goals; and have the capacity in management structures to adapt either the goals or the flow regime if the monitoring results indicate this is necessary.

3. USING MULTI-CRITERIA ANALYSIS TO DEVELOP ENVIRONMENTAL FLOW SCENARIOS FOR RIVERS TARGETTED FOR WATER-RESOURCE MANAGEMENT

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3.1 Publication details

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3.2 Introduction

Environmental flows may be defined as water that is left in a river system, or released into it, for the specific purpose of managing the condition of that ecosystem. During the last five decades, about 100 different approaches have been described for advising on environmental flows, and more than 30 countries have begun to use such assessments in the management of water resources (Tharme 1996; King *et al. 1*999).

There are essentially two kinds of approaches to flow assessments: prescriptive and interactive (Brown & King 2002b). Prescriptive methods usually address a narrow and specific objective in terms of river condition and result in a recommendation for a single flow value or flow regime to achieve it. Their outcomes tend not to lend themselves to negotiation, because insufficient information is supplied on the implications of *not* meeting the recommended value to allow an informed compromise (Stalnaker *et al*. 1995). Interactive approaches, on the other hand, focus on the relationships between changes in river flow and one or more aspects of the river ecosystem. Once these relationships are established, the debate is no longer restricted to a single interpretation of what the resulting river condition would be. Methods based on the interactive approach are thus better suited for creating scenarios to be used in negotiations.

DRIFT (Downstream Response to Imposed Flow Transformations) is an interactive, holistic (Tharme 1996) approach to advising on environmental flows for rivers (Figure 3.1), developed from earlier holistic methodologies (King & Louw 1998), through several applications in southern Africa. It is described in detail in King *et al.* (2003). The methodology allows data and knowledge to be used to their best advantage within a structured process. The central rationale of DRIFT is that different parts of the flow regime, e.g., lowflows, and small, medium and large floods, maintain different parts of the river ecosystem. Thus, manipulation of one or more kinds of flow will affect the ecosystem differently than manipulation of some other combination. In its totality, DRIFT consists of four modules (biophysical, subsistence use, scenario development and compensation economics, Figure 3.1). In the first, or biophysical module, the river ecosystem is described and predictive capacity developed on how it would change with flow changes. In the second, or subsistence module, links are described between riparian people who are common-property subsistence users of river resources, the resources they use, and their health. The objective is to develop predictive capacity of how river changes would impact their lives. In the third module, scenarios are built of potential future flows and of the predicted impacts of these on the river and the riparian people. The fourth, or compensation-economics, module lists compensation and mitigation costs (King *et al*. 2003).

This paper concentrates on the first part of the third module, in which the outputs from the biophysical module are used with multicriteria analysis (MCA) to create the flow scenarios and their biophysical consequences (Figure 3.1). The essential features of DRIFT, the output of DRIFT work sessions and the development of the DRIFT database are described. The use of MCA within the database, specifically within the DRIFTSOLVER and DRIFT CATEGORY routines, to generate flow scenarios and evaluate them in terms of river condition is then explained and illustrated using examples.

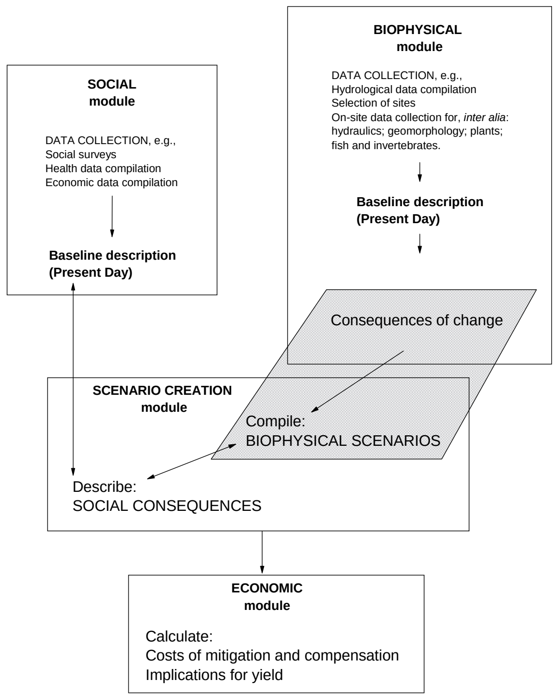

Figure 3.1. DRIFT modules (after King *et al*. 2003) and illustration of the area of focus of this paper (shaded).

3.3 Essential features of DRIFT

DRIFT has several features that impart structure to specialist deliberations on the consequences of flow changes (King *et al*. 2003). Data collection and subsequent deliberations are centred on river sites, each of which is representative of a river reach. The present-day long-term daily flow data for each site are separated into ten flow classes (Table 3.1), and specialists predict the consequences of up to four levels of change from present condition in each flow class for different components of the river ecosystem. The ecosystem components that are routinely considered are fluvial geomorphology, water quality, plants, aquatic invertebrates and fish (Table 3.1), but depending on the river under study additional components, such as mammals, birds and herpetofauna, can be added. The descriptions of biophysical consequences of flow changes are usually built up in a sequence starting with geomorphology, then water quality and thereafter vegetation, invertebrates, fish, bird and other wildlife, with each specialist remains responsible for her/his own area of expertise.

Table 3.1. Flow classes that are reduced, or increased, in magnitude or number, to produce described consequences, and the five ecosystem components for which consequences are routinely predicted. See King *et al.* (2003) for details.

Flow class	Consequences described for:	Ecosystem component
1. Dry-season low flow (range)	4 levels of increase/decrease	1. Fluvial geomorphology 2. Water quality 3. Plants 4. Aquatic invertebrates 5. Fish The hydraulics of the river channel are also computed.
2. Wet-season low flow (range)		
3. Intra-annual floods: Class 1	4 changes in the number per annum	
4. Intra-annual floods: Class 2		
5. Intra-annual floods: Class 3		
6. Intra-annual floods: Class 4		
7. 1:2 year flood (Class 5)	Presence or absence	
8. 1:5 year flood (Class 6)		
9. 1:10 year flood (Class 7)		
10. 1:20 year flood (Class 8)		

When recording the consequences of each considered flow change, the specialists consider any number of sub-components that may be relevant to their ecosystem components (Table 3.2, King *et al*. 2003). For each considered flow change at each study site, the affect on every sub-component is described. Sub-components may comprise channel (physical) features, chemical features, communities or individual species, and are chosen because of their known susceptibility to flow changes, their role as key species or features, or their relevance to subsistence users.

Table 3.2. Ecosystem components, and possible sub-components

Component	Sub-components
Geomorphology	Colloidal material; pools; riffles; sand bars
Water quality	pH; temperature; suspended solids; nutrient concentrations
Vegetation	Algae; floating aquatics; rooted aquatics; wetbank zone community; drybank zone community
Invertebrates	*Simulium nigritarse; Baetis harrisoni*; riffle community
Fish	largemouth yellowfish; serial spawners

The output of DRIFT work session is therefore a matrix of consequences, completed by the specialists, for a range of possible reductions (or additions) in the ten flow classes (Table 3.1), which is entered into the DRIFT database (Figure 3.2), together with information on the data sources used. Each consequence is accompanied by a Severity Rating (Table 3.3), which indicates (1) if the sub-component is expected to *increase* or *decrease* in abundance, magnitude or size; and (2) the *severity* of that increase/decrease, on a scale of 0 (no measurable change) to 5 (very large change). The scale accommodates uncertainty, as each rating encompasses a range in percentage gain or loss. Greater uncertainty can be expressed through providing a range of severity ratings (i.e., a range of ranges) for any one predicted change (after King *et al.* 2002). To assist with the eventual placement of flow scenarios within a classification of overall river condition, the Severity Ratings are taken further to indicate whether that change would be a shift toward or away from the natural condition. The Severity Ratings hold their original numerical value of between 0 and 5, but are given an additional negative or positive sign, to transform them from *Severity Ratings* (of changes in abundance or extent) to *Integrity Ratings* (of shift to/away from naturalness), where:

- *toward natural* is represented by a positive Integrity Rating; and
- *away from natural* is represented by a negative Integrity Rating.

In summary, each entry within the database consists of (Table 3.4):

- a site name
- a flow reduction from (or addition to) the present-day status of one of the low or high flow classes (e.g., presently an average of four Class 2 floods per annum: reduce to two per annum);
- the consequences of this for a range of ecosystem components (e.g., plants) and their sub-components (e.g., algae), expressed as:
    - the direction of predicted change (increase or decrease)
    - the extent of change (Severity Rating)
    - the expected impact on river condition, relative to natural (Integrity Rating)
    - descriptions of the ecological and social significance of the predicted change;
- the volume of water required to deliver this flow, expressed as $m^3 \times 10^6$ for each of the ten flow classes, per season and per annum.

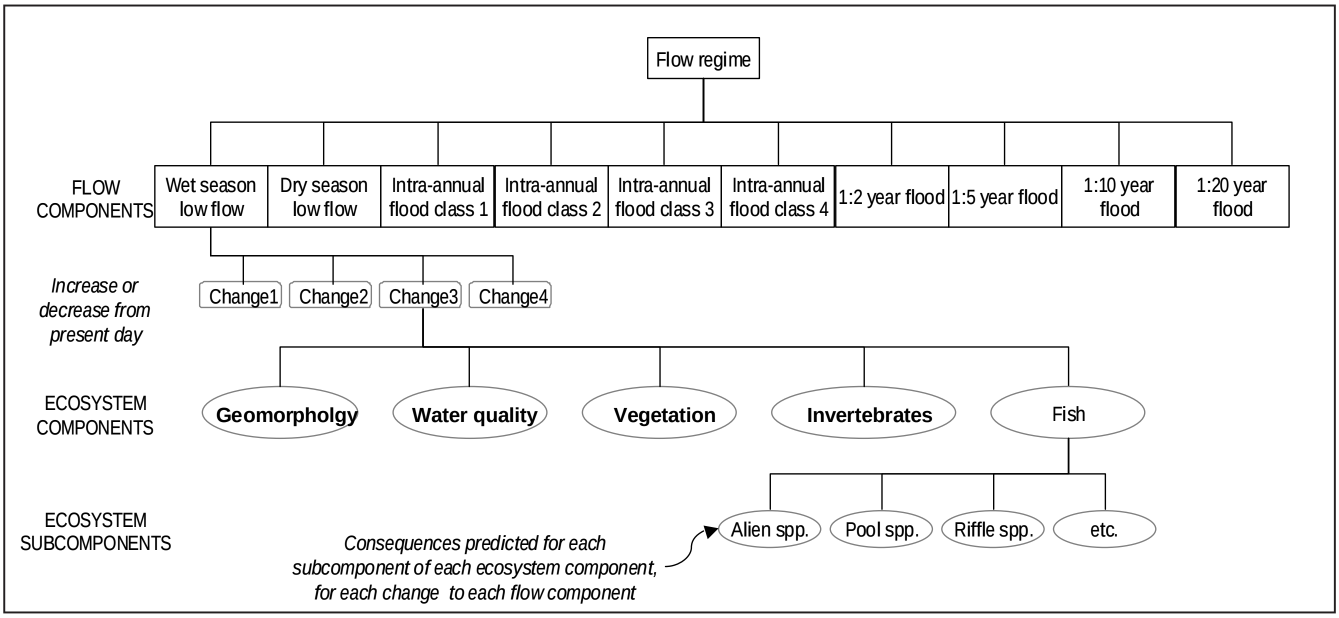

Figure 3.2. Framework for the database of consequences of reductions or additions in low or high flows for ecosystem sub-components.

Table 3.3. Severity Ratings for each prediction of flow-related change. Severity Ratings convert directly to Integrity Ratings by adding a + (toward natural) or a – (away from natural).

Severity rating	**Severity of change**	**Equivalent loss** (abundance/concentration)	**Equivalent gain** (abundance/concentration)
0	None	no change	No change
1	Negligible	80-100% retained	1-25% gain
2	Low	60-79% retained	26-67% gain
3	Moderate	40-59% retained	68-250% gain
4	Severe	20-39% retained	251-500% gain
5	Critically severe	0-19% retained; includes local extinction	501% gain to ∞: up to pest proportions

Table 3.4. Example of a consequence entry in the database for one ecosystem sub-component.

Type of information	**Information**
Site	2
Flow change level	Reduction level 4 of dry-season low flows
Component	Invertebrates
Sub-component	*Simulium nigritarse*
Direction of change in abundance	Increase
Severity Rating	5: critically severe
Integrity Rating	–5: away from natural
Ecological significance	Filter feeder in slow, eutrophic water
Social significance	Blood-sucking pest of poultry
Volume of water	12 m^3 x 10^6 per annum

3.4 Use of multi-criteria analysis in DRIFT

The number of separate consequence entries comprising the DRIFT database for a river site varies depending on the level of detail at which a flow assessment is done but is seldom less than 1000 (Brown & King 2002a), and can be high as 30 000 (Metsi Consultants 2000g). These are used to create any number of scenarios by combining one change level from each flow class. The complexity, and possible permutations for recombination, require a coherent framework for evaluation of flow scenarios that lends itself to a mathematical programming approach. The relevant scenario creation and evaluation worksheets in the database are DRIFTSOLVER and DRIFT CATEGORY.

3.5 DRIFTSOLVER

The consequence data can be combined in DRIFTSOLVER in a range of permutations to create new flow regime scenarios, together with their ecosystem consequences and the implications for yield of water. There are three starting points for the generation of such flow scenarios, referred to here as TYPE 1 – 3.

TYPE 1: A SPECIFIED VOLUME OF WATER AVAILABLE FOR ENVIRONMENTAL FLOWS. The scenario will describe the predicted condition of the river when a given volume of water is distributed optimally between selected change levels for the different classes of flow on the basis of their effect on overall ecosystem condition.

TYPE 2: A SPECIFIED CONDITION IN WHICH THE RIVER SHOULD BE MAINTAINED. The scenario will describe the amount of water and optimal distribution required to facilitate maintenance of the river in the desired condition.

TYPE 3: MANAGEMENT LIMITATIONS: TYPE 1 OR TYPE 2 with modifications on the basis of limitations imposed by management or design constraints. The scenario will describe the volume and condition of the river resulting from non-optimal distribution of water between different flow classes.

3.5.1 Compiling a TYPE 1 flow scenario using integer linear programming

The DRIFTSOLVER routine uses the Solver tool in Excel, which provides the necessary ("branch and bound") algorithm (Microsoft 1985-1997). An integer linear program (e.g. Winston 1994) optimises the distribution of a given total volume of water among different the change levels of flow classes in a way that results in the lowest aggregate impact on the riverine ecosystem according to the Integrity Ratings. It does this by summing the Integrity Ratings of all the sub-components, taking into account all the negative or positive signs, to produce combinations of high and low flows that return the highest possible Overall Integrity Score for that volume.

The Overall Integrity Score for a particular flow scenario is obtained by summation in three steps. The mathematical notation used is given in Table 3.5.

Table 3.5. Mathematical notation used in this paper.

Notation	Designation	Range
i	Flow classes	1 to 10 (see Table 3.1)
m	Ecosystem components	1 to ≥ 5 (see Table 3.1)
k	Ecosystem sub-component	1 to n, for each m
j	Change level for each flow class	0*, 1, 2, 3, or 4 for each **i**
$\mathbf{x_{ijk}}$	Sub-component Integrity Rating, i.e., the effect on integrity of flow class **i** at change level **j**, on ecosystem sub-component **k**	-5 to +5
$\mathbf{X_{ijm}}$	Component Integrity Rating, i.e., the effect on integrity of flow class **i** at change level **j**, on ecosystem component **m**	-5 to +5
$\mathbf{z_{ij}}$	Flow Level Integrity Score, i.e., the effect on integrity of flow class **i** at change level **j**, on the whole riverine ecosystem	-5 to +5
Z	Overall Integrity Score, i.e., expected river condition for a flow scenario	0 = Present Day, +ve = rehabilitation; -ve = degradation
$\mathbf{I_{ij}}$	Binary code used to denote the change level chosen for a particular flow class.	1 if flow reduction level *j* is chosen for flow class *i*, if not = 0

* Present day levels.

STEP 1 The sub-component Integrity Ratings ($\boldsymbol{x}_{ijk}$) for a flow change level are aggregated (weighted sum) for each ecosystem component to give a score for that component ($\boldsymbol{X}_{ijm}$). For example, applying the numbers in Table 3.1 to the notation in Table 3.5, the Fish Integrity Rating for change level 2 in wet season lowflows would be $\boldsymbol{X}_{225}$, and if four species (sub-components) were considered, the Fish Integrity Rating would be the weighted sum of their Integrity Ratings ($\boldsymbol{x}_{22k;}$ where k=1,4):

$$X_{ijm} = \sum_{k=1}^{n} w_k \, x_{ijk} \,, \quad \text{where } w_k \text{ is the weight of ecosystem sub-component } k \quad \mathbf{(1)}$$

STEP 2 The five ecosystem component scores are aggregated to arrive at the Flow Level Integrity Scores ($\boldsymbol{z}_{ij}$) for each flow class change:

$$z_{ij} = \sum_{m=1}^{5} W_m \, X_{ijm} \,, \quad \text{where } W_m \text{ is the weight of ecosystem component } m \quad \mathbf{(2)}$$

STEP 3 The Flow Level Integrity Scores ($\boldsymbol{z}_{ij}$) for all 10 flow classes (Table 3.1) are aggregated to give an Overall Integrity Score $\boldsymbol{Z}$ for a particular flow scenario, e.g., $\boldsymbol{Z}_{scenarioA}$:

$$Z_{scenarioA} = \sum_{i=1}^{10} \omega_i \, z_{ij} \,, \quad \text{where } \omega_i \text{ is the weight of flow class I} \quad \mathbf{(3)}$$

The flow levels *j* that are selected for each flow class *i* are denoted by the indicator variable (I_{ij}). The problem can then be expressed as maximising the Overall Integrity Score $\boldsymbol{Z}$:

$$Z = \sum_{i=1}^{10} I_{ij}\omega_i z_{ij} \quad ,$$ where I_{ij} is either 0 or 1 for the particular flow change j. **(4)**

The I_{ij} are binary (or 0-1 integer) variables, and DRIFTSOLVER is set up to maximise the aggregate score *Z* by choosing the I_{ij} for each flow class (i.e., choosing which flow change is selected for each flow component). Only one $I_{ij} = 1$ is allowed for each flow class *i* by setting the constraint:

$$\sum_{j=1}^{4} I_{ij} = 1$$ **(5)**

For change levels that are not selected as part of the flow regime I_{ij} =0 and the contribution to equation 4 is zero.

For TYPE 1 scenario analyses, a total volume (Q) is specified, which must be distributed between the flow classes. DRIFTSOLVER runs through each of the possible flow changes and either accepts or rejects it by setting $\mathbf{I}_{ij}$ to 1 or 0. DRIFTSOLVER sums the volumes used (q_{ij}) by each flow change level and checks that the summed volume Q* is within a user-specified range of the given total volume Q (e.g. 90% Q ≥ Q* ≤ 110% Q). There is therefore an overall constraint that:

$Q \times a \geq Q^* \leq Q \times b$, **(6)**

where $Q^* = \sum_{i=1}^{10} \sum_{j=1}^{4} I_{ij} q_j$ and *a* and *b* are allowed deviations from the allocatable total Q.

Acceptance or rejection of a change level for a flow class is therefore based on a trade-off between the volume required and the score z_{ij} for that flow class *i* level *j*.

In summary, DRIFTSOLVER solves the following problem:

Maximise: ***Z*** (Equation 4), where ***Z*** is built up from equations 1, 2 and 3;
subject to the constraints of equations 5 and 6, and all I_{ij} = 0,1.

An example is given in the next section, followed by a discussion of ways in which flow scenarios can be analysed subsequent to their development as described above.

Example

To illustrate the application of the equations, an example is given based on the values from Site 2 on the Molenaars River in the Western Cape, South Africa (Table 3.6). DRIFTSOLVER was applied to find the optimal distribution of an initial specified total volume Q of 77×10^6 m^3a^{-1}. The resulting scenario is presented in Table 3.6 (shaded levels) and is comprised of the following change levels from present day:

1. Wet season lowflows: Change level 1.
2. Dry season lowflows: Change level 1.
3. Class 1 Floods: Change level 1.

4.	Class 2 Floods:	Change level 1.
5.	Class 3 Floods:	Change level 2.
6.	Class 4 Floods:	Change level 1.
7.	1:2 YEAR:	Change level 1.
8.	1:5 YEAR:	Change level 1.
9.	1:10 YEAR:	Change level 1.
10.	1:20 YEAR:	Change level 0.

The Overall Integrity Score (Z) is -0.218 and Q* (summed volume) is 80.5×10^6 m^3a^{-1}. In other words, the optimal arrangement of a total volume of water of Q* = 80.5×10^6 m^3a^{-1} would yield an Integrity Score (***Z***) of -0.218, which represents a shift away from natural.

We use the five rows applying to Class 2 floods to explain Table 3.6. The first row represents present day conditions, reflecting the present day number of Class 2 floods. Each of the following four rows corresponds to a flow reduction level (no augmentations were considered in this example) reflecting reductions in the number of Class 2 floods. Column 3 shows the chosen change level (1 = selected, 0 = not selected). Column 4 is the volume of water required for each change level. Columns 5 to 9 are the ecosystem component Integrity Ratings (X_{4jm}, m=1 to 5), each of which is a weighted sum of ecosystem subcomponent Integrity Ratings (not shown). So for flow reduction level 1 of the Class 2 floods, the water quality (m=2) Integrity Rating is –0.3.

The combined Integrity Ratings (z_{ij}) for each flow change level are shown in Column 10. These are the weighted sums of the ratings in Columns 5 to 9 using the weights shown in Row 2. For the Class 2 floods, Change Level 1:

$\mathbf{z}_{41} = (W_1 \times X_{411}) + (W_2 \times X_{421}) + (W_3 \times X_{431}) + (W_4 \times X_{441}) + (W_5 \times X_{451})$

$= (0.2 \times 0) + (0.2 \times -0.3) + (0.2 \times 0) + (0.2 \times -0.3) + (0.2 \times 0) = -0.12$ (bold in Table 3.6).

The combined Integrity Rating for the chosen change level for each flow class is shown in Column 11, together with the corresponding volume of water in brackets: Change Level 1 for Class 2 floods would require 5.4 MCM. Column 12 shows the weight ω_j applied to each flow class. The weighted contribution of Class 2 floods to the Overall Integrity Score is given in Column 13. The Overall Integrity Score is the sum of Column 13. This is a sum of the contributions of all the classes of the flow regime:

$Z = -0.02 + -0.02 + -0.01 + -0.02 + -0.06 + -0.01 + -0.06 + -0.01 + -0.01 + 0$

$= -0.218.$

Table 3.6. Example of a flow scenario for Site 2 on the Molenaars River (natural Mean Annual Runoff (MAR) = 160 × 10^6 m^{3}a^{-1} and present day MAR = 145 × 10^6 m^{3}a^{-1}). Integrity Ratings X_{ijm} for each flow reduction level and for the chosen reduction level, and the Overall Integrity Score Z are shown. PH = physical habitat, WQ=water quality, Veg=Vegetation, MI=macro-invertebrates. For explanation, see text.

1	2	3	4	5	6	7	8	9	10	11	12	13
Flow class i				**Ecosystem component X_{ijm}**					$z_{ij}=\sum_{m=1}^{5} W_m X_{ijm}$	$I_{ij}z_{ij}$ ($I_{ij}q_{ij}$)	ω_i	$\omega_i z_{ij}$
				W_m 0.2	0.2	0.2	0.2	0.2				
	j	**I_{ij}**	**q_{ij}**	**PH**	**WQ**	**Veg**	**MI**	**Fish**				
1=Wet season low flow	0	-0	47	0	0	0	0	0	0	-0.15 (31.8)	0.16	-0.02
	1	1	31.8	0	-0.8	0	0	0	-0.15			
	2	0	24.6	-1	-1.4	-1.7	0	-1	-1			
	3	0	12.8	-2.5	-1.9	-3	-2	-2	-2.28			
	4	0	5.28	-3.5	-1.9	-4	-3	-3.7	-3.21			
2=Dry season low flow	0	-0	17	0	0	0	0	0	0	-0.15 (8.9)	0.16	-0.02
	1	1	8.9	0	-0.8	0	0	0	-0.15			
	2	0	6.8	-1	-1.4	-2	0	-1	-1.01			
	3	0	4.5	-2.5	-2	-3	-2	-2	-2.29			
	4	0	2.7	-3.5	-2	-4	-3	-4	-3.2			
3=Flood Class 1	0	-0	5.6	0	0	0	0	0	0	-0.05 (3.5)	0.16	-0.01
	1	1	3.5	0	-0.3	0	0	0	-0.05			
	2	0	2.1	0	-0.4	-0.7	0	-0.5	-0.32			
	3	0	0.7	0	-1	-1	-0.5	-0.7	-0.63			
	4	0	0	0	-1.3	-1.3	-1.2	-0.7	-0.88			
4=Flood Class 2	0	0	8.2	0	0	0	0	0	0	**-0.12 (5.4)**	**0.16**	**-0.02**
	1	1	5.4	0	-0.3	0	-0.3	0	**-0.12**			
	2	0	2.7	0	-0.5	-0.50	-0.8	0	-0.37			
	3	0	0	0	-1.1	-0.8	-2.2	-3	-1.41			
	4	0	0	0	-9	-9	-9	-9	-7.2			
5=Flood Class 3	0	0	21	0	0	0	0	0	0	-0.35 (5.2)	0.16	-0.06
	1	0	10.4	0	-0.1	-0.2	-0.2	0	-0.09			
	2	1	5.2	0	-0.4	-0.5	-0.8	0	-0.35			
	3	0	0	0	-0.9	-0.7	-2.2	-3	-1.34			
6=Flood Class 4	0	0	36	0	0	0	0	0	0	-0.09 (24)	0.16	-0.01
	1	1	24	0	-0.13	-0.17	-0.17	0.00	-0.09			
	2	0	12	0	-0.25	-0.67	-0.83	-1.50	-0.65			
	3	0	0	-4	-0.50	-0.92	-2.00	-2.50	-1.98			
7=1:2 year flood	0	0	10.6	0	0	0	0	0	0	-1.6 (0)	0.04	-0.06
	1	1	0	-4	0	-4	0	0	-1.6			
8=1:5 year flood	0	0	6.5	0	0	0	0	0	0	-0.8 (0)	0.01	-0.01
	1	1	0	-4	0	0	0	0	-0.8			
9=1:10 year flood	0	0	3.3	0	0	0	0	0	0	-0.8 (0)	0.01	-0.01
	1	1	0	-4	0	0	0	0	-0.8			
10=1:20 year flood	0	1	1.65	0	0	0	0	0	0	0 (1.65)	0.01	0
	1	0	0	-4	0	0	0	0	-0.8			
		Q*=	80.45						**$Z_{scenarioA}$ =**	$\sum_{i=1}^{10}\omega_i z_{ij}$	=	-0.218

3.5.2 Weights

The option for using weights, which will alter the contribution made by individual scores, has been included in DRIFTSOLVER at three different levels: ecosystem sub-component w_k, ecosystem component W_m and flow class ω_l (Figure 3.2). As the Overall Integrity Score Z is made up of a number of weighted summations, the weights allocated at any one level will affect the trade-offs made (by DRIFTSOLVER) and, thus, affect the flow regime ultimately chosen. Additionally, the rationale for and importance of allocating weights is different for each level. Weights, therefore, should be allocated with care and should be based on detailed discussion with and between specialists for each of the sub-components. There are MCA techniques available that can be used to elicit appropriate weights from specialists but these have not yet been applied during the development of DRIFTSOLVER. Thus, to avoid confusion, the weights were kept equal in the examples presented here, except for the floods with return periods of 1:5, 1:10 and 1:20 years, which were allocated lower weights than the rest as they would overtop the dams and so do not form part of the requested releases for environmental flows.

Equal weights are only one of a set of possible weights reflecting perceived importance in determining river condition and do not imply a more ‘objective’ system. It may be, for instance, that an increase of Simuliidae to pest proportions would have an overriding effect on the integrity of the macroinvertebrate community, and so it could be weighted heavily to ensure flows are selected that do not favour its proliferation. Initial analyses of the example shown here suggest that results will be fairly robust to changes in weights, but sensitivity analysis needs to be done. This is the subject of another paper.

3.5.3 Compiling TYPE 2 and 3 flow scenarios

The procedures for Types 2 and 3 scenarios are similar to that described for Type 1, although they involve slightly more manipulation of the database, for instance, targeting a specific river condition (Type 2) or excluding some flow classes or change levels from consideration (Type 3).

3.6 DRIFT CATEGORY

By rerunning DRIFTSOLVER for a Type 1 scenario with incremental increases of the percent MAR available for river maintenance, several scenarios can be created. For each scenario, the percentage of naturalised MAR is plotted against its Overall Integrity Score, to provide a graphic of the link between river condition and water volume (Figure 3.3). This constitutes the basic DRIFT CATEGORY output. The zero on the vertical axis represents the Present Ecological State (PES; DWAF 1999) of the river. Scenarios below that, with a negative Integrity Score, would move the river ecosystem away from natural, whilst those above, with a positive Integrity Score (not illustrated in Figure 3.3) would move it toward natural.

The graph can be used to examine the relationship between volume of water and ecosystem integrity, identify features, such as inflection points, where integrity changes considerably for a small change in flow. It can be used to appraise the sensitivity of DRIFTSOLVER to changes in sub-component Integrity Ratings, or weights. Scenarios can also be generated and plotted to evaluate the implications of non-optimal distribution of flows, such as may happen where large floods (e.g., > Class 2 floods) cannot be released through an upstream dam. In the case of the Molenaars River, for instance, if such constraints were placed on the temporal distribution of flows, then the river condition that could be achieved with *c*. 50 % of the MAR allocated sub-optimally to the river, would be no better than that which could be achieved by allocating *c*. 30 % optimally (Figure 3.3).

As stated earlier, specialists' uncertainties in their predictions are expressed as a range of possible Integrity Ratings at the sub-component level. The error bars in the DRIFT CATEGORY output (Figure 3.3) represent the predicted maximum and minimum Overall Integrity Scores associated with each scenario, and are calculated from the ranges of Integrity Ratings given by the specialists. The estimated range (therefore uncertainty) increases with distance from the present day flow regime and condition. This is an expected phenomenon, as specialists feel able to predict most accurately those flow manipulations that will change the river to a small extent.

3.6.1 Relation to South African River Categories

Once the basic DRIFT CATEGORY output has been generated, it should be possible to link the scenarios depicted to some categorisation or classification of river condition, since at some point along the vertical axis, the scenarios will move the river into another condition category. A potential linkage to the South African River Categories A to F (Table 3.7; DWAF 1999; Kleynhans 1996) is used to illustrate this concept. In the example given in Figure 3.3, the PES of the river (zero on vertical axis), as assessed by the specialists, was Category B (Brown and King 2002c). Starting from PES, a scenario with a negative Integrity Score would represent movement in the direction of a Category C-F river, whilst one with a positive score would indicate movement toward a Category A river.

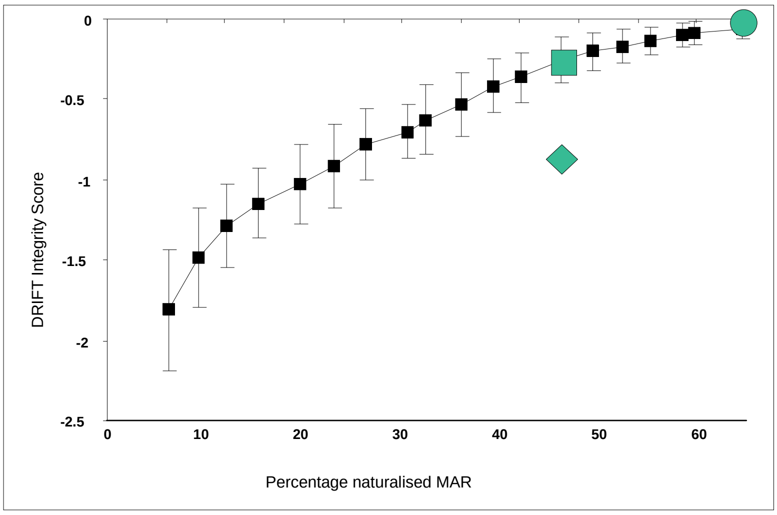

Figure 3.3 **The basic DRIFT CATEGORY output for Site 2 on the Molenaars River, Western Cape (Brown & King 2002c) showing changes in Overall Integrity Rating for different percentages of MAR.** Circle: Present Ecological State (PES); square: the (optimal) position of the scenario given in Table 3.6; diamond: the position of a (non-optimal) scenario in which 50 % of the natural MAR was allocated to the river but where an upstream dam could not release Class 2 to Class 4 floods or 1:2 year floods, i.e., sub-optimal distribution (i.e. a Type 3 scenario).

Table 3.7. The South African River Categories (DWAF 1999).

CATEGORY	DESCRIPTION
A	Unmodified, natural.
B	Largely natural with few modifications. A small change in natural habitats and biota may have taken place but the ecosystem functions are essentially unchanged.
C	Moderately modified. A loss and change of natural habitat and biota have occurred but the basic ecosystem functions are still predominantly unchanged.
D	Largely modified. A large loss of natural habitat, biota and basic ecosystem functions has occurred.
E	The loss of natural habitat, biota and basic ecosystem functions is extensive.
F	Modifications have reached a critical level and the lotic system has been modified completely with an almost complete loss of natural habitat and biota. In the worst instances the basic ecosystem functions have been destroyed and the changes are irreversible.

At this stage, there is no clear definition of when a river shifts from one category to the next. Nor is the kind of Integrity Score that would indicate such a shift known. In the absence of known functional links between Integrity scores and Categories, a pragmatic approach is to develop a set of generally acceptable and applicable heuristics. As a first contribution to this discussion, the following general rules have been used. The examples that follow illustrate the effects of changing the distribution of volume from optimal to non-optimal on river condition category as defined by these rules.

Scenarios that shift an ecosystem back toward natural

If, for a given scenario, the final score of all the Integrity Ratings for all sub-components (i.e., Overall Integrity Score) is positive and:

- if at least 85% of the individual Integrity Ratings are ≤ 1, then the ecosystem will remain in the present category (e.g., Category B for the Molenaars River);
- if at least 85% of the individual Integrity Ratings are ≤ 2, then the ecosystem will shift to the next highest category (e.g., Category B (present) to Category A (predicted) for the Molenaars River);
- if at least 85% of the individual Integrity Ratings are ≤ 3, then the ecosystem will shift to two categories higher (not applicable for the Molenaars River);
- if at least 85% of the individual Integrity Ratings are ≤ 4, then the ecosystem will shift to three categories higher (not applicable for the Molenaars River).

Scenarios that shift an ecosystem away from natural

If, for a given scenario, the Overall Integrity Score is negative and:

- if at least 85% of the individual Integrity Ratings are ≥ -1, then the ecosystem will remain in the present category (e.g., Category B for the Molenaars River);
- if at least 85% of the individual Integrity Ratings are ≥ -2, then the ecosystem will shift to the next lowest category (e.g., Category B (present) to Category C (predicted) for the Molenaars River);
- if at least 85% of the individual Integrity Ratings are ≥ -3, then the ecosystem will shift to two categories lower (e.g., Category B (present) to Category D (predicted) for the Molenaars River);
- if at least 85% of the individual Integrity Ratings are ≥ -4, then the ecosystem will shift to three categories lower (e.g., Category B (present) to Category E (predicted) for the Molenaars River).

In the DRIFT CATEGORY outputs (Figure 3.4 and 3.5), the boundaries between the South African River Categories are shown as faded lines, as they will tend to be indefinite “zones” rather than clear boundaries. Figure 3.4 indicates the boundaries between the SA River Categories for Site 2 on the Molenaars River, as determined using the rules given above. In this example, it is expected that 50% of the natural MAR (e.g., square in Figure 3.4), distributed optimally would maintain the river in Category B, i.e., near its PES. However, if the distribution of this volume of water was not possible then the condition of the river would tend toward some other category dictated by the actual flow distribution (diamond in Figure 3.4).

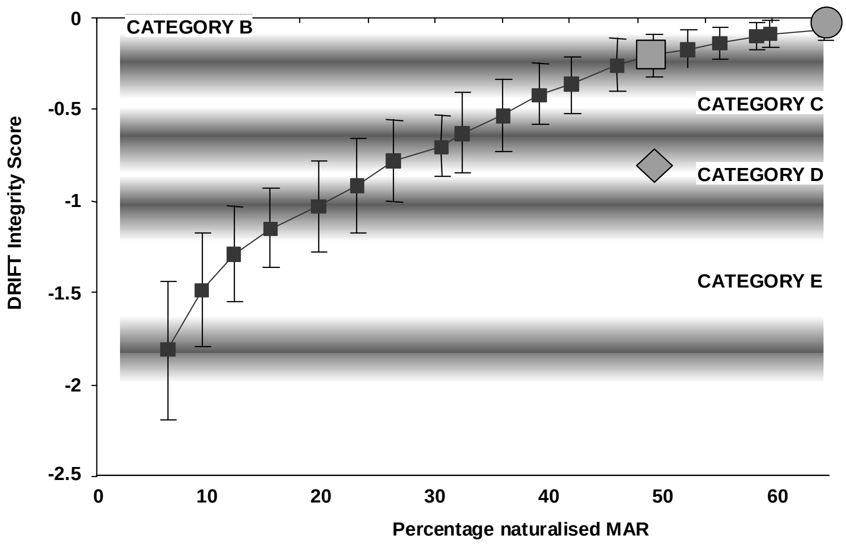

Figure 3.4 DRIFT CATEGORY output for Site 2 on the Molenaars River, Western Cape showing River Condition Categories

Figure 3.5 gives the DRIFT CATEGORY output for a site on the middle Breede River, Western Cape. In this example, the PES of the river is Category D/E (zero on the y-axis, circle in The Breede River, as represented by this site, is naturally perennial. The river presently receives c. 80% of its naturalised MAR, but run-of-river abstraction during the summer results in no-flow conditions in the river for much of the dry season. The DRIFT CATEGORY results indicate that improving the distribution of flows in the river by reinstating some of the dry-season lowflows would lead to an improvement in overall condition, toward a D, or even a C/D, Category. Improvement beyond that point would be prevented by non-flow related impacts on the river such as bulldozing in the flood plain and invasion of alien vegetation in the riparian zone (Brown & Louw 2001). An overall decline in condition, i.e., negative Overall Integrity Score, would lead to an E (or lower) category river.

3.7 Links to the subsistence and economic modules

The DRIFT CATEGORY outputs facilitate the standardised development of summary scenarios and links these to levels of river condition. These scenarios are intended for use in the decision-making process. The level of detail they provide is sufficient to inform the sort of broad-level tradeoffs that are usually required to balance potentially conflicting uses such as environmental protection versus agricultural development, but is backed up by the detailed predicted consequence data received from the specialists. It is possible to extract the data behind the summaries to provide a detailed description of river change for any scenario.

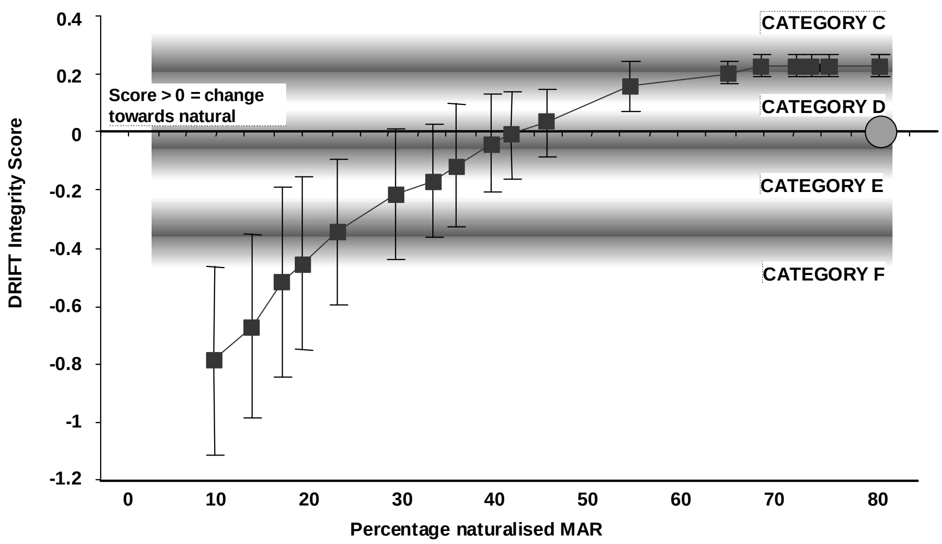

Figure 3.5. DRIFT CATEGORY output for a site on the middle Breede River.

Such detailed descriptions are required to determine the socio-economic consequences for subsistence users of the river's resources. All the uses made of rivers ultimately depend on the biophysical processes in those rivers. Thus, potential flow-related changes in ecosystem sub-components are used as the template for predicting social impacts and their economic implications. The socio-economic procedures are addressed to some extent in King *et al*. (2003) and form part of the on-going development of DRIFT.

3.8 Summary of the DRIFT database

The DRIFT database comprises six Excel worksheets that can be loosely divided into two groups, *viz*. data storage and scenario creation and evaluation (Figure 3.6). In summary, two types of MCA are used to create and manipulate the data in the database. The raw consequence data are generated using a value measurement approach (e.g., Stewart *et al*. 2001) and integer linear programming (Winston 1994) is used in DRIFTSOLVER to recombine these flow classes into a modified flow regime.

The DRIFT CATEGORY output depicts river condition at the level of the whole ecosystem, relative to its current state, and the volumes provided are the maximum annual volume required to acheive each scenario. The shape of the graph is specific for the river site under its present flow and management conditions, and is based on the "least-damaging" mix of high and low flows.

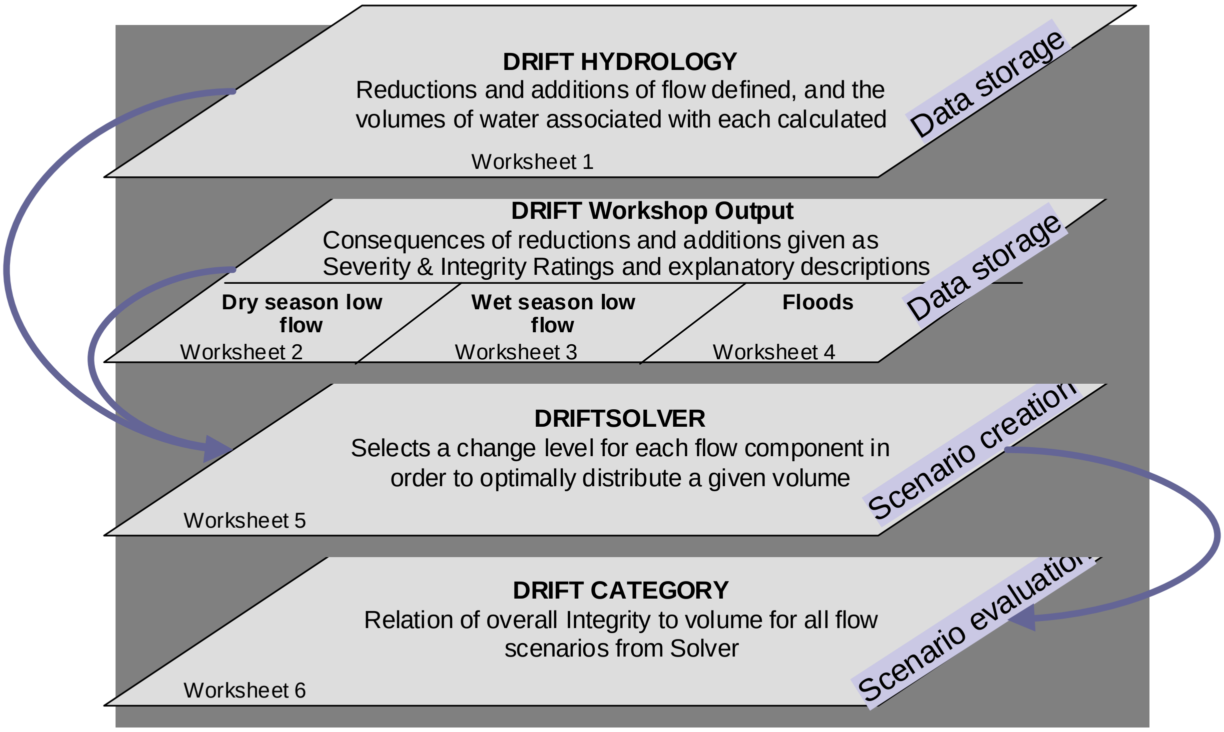

Figure 3.6 **The Excel worksheets within the DRIFT database**.

3.9 Discussion

In the field of environmental flow assessment and allocations, science forms only one part of much of the work required. A major challenge is to ensure that good science translates into good management. Thus, scientific outputs should be converted into easily digestible formats that can be quickly absorbed and used by decision makers who must take into account a wide variety of competing needs for water.

The DRIFT methodology structures and maximises the information gathered from specialists during environmental flow assessment workshops. The DRIFT database provides a permanent record of the flow-related information used for a particular system and the pathway used to develop the flow scenarios is transparent, from raw data through to a final scenario. When a scenario is decided upon, its flow regime becomes the environmental flow and the river condition it represents becomes the agreed desired state. The predictions from the chosen scenario provide the criteria to be measured in a follow-up monitoring programme.

Additionally, numerous scenarios linking future flow regimes to predicted river condition can be generated quickly and easily, and in so doing can provide data for regional calibration of rapid environmental flow models, such as the South African Desktop Model for Reserve Determinations (DWAF 1999).

Further development of DRIFT includes refinement of the lists of sub-components and components used by the specialists into a generic list, attention to assigning weights that reflect the contributions of different sub-components to overall river condition, further development and calibration of DRIFT CATEGORY and incorporation of subsistence use data into DRIFTSOLVER.

4. GENERIC LISTS FOR USE IN DRIFT ASSESSMENTS

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4.1 Introduction

Holistic methodologies for assessing environmental flows, such as DRIFT, were developed in order to overcome some of the problems associated with habitat-rating methods (e.g. IFIM, Bovee 1982). Habitat-rating methods focus on a single species or species group of important recreational or economic value - usually fish - and do not necessarily address the consequences of flow changes on other parts of the ecosystem (e.g. aquatic invertebrates, riparian vegetation, algae) that are also flow dependent and that might be supporting the targeted species. As a holistic methodology, DRIFT considers all the major abiotic and biotic components of the riverine ecosystem and their likely responses to the full spectrum of natural flows and flow changes in the river.

The biophysical module of DRIFT requires that empirical data, conceptual or predictive models and expert opinion of flow-related ecosystem processes be transformed into semi-quantitative descriptions of how increments of flow change could cause increments of river change. The quantity of data that needs to be processed in order to do this, its complexity because of the interrelatedness of constituent components, and the degree of inter-disciplinary exchange needed between specialists, makes the definition of all possible ecosystemic changes extremely complex.

Generic lists were proposed as a means of guiding specialists in their considerations, and to facilitate the orderly input of information into DRIFT-SOLVER (Chapter 3). They were intended as simple lists that would indicate which river variables were important in ecosystem functioning and were sensitive to changes in flow. In a DRIFT workshop, each specialist would first compile her/his list and then, for each considered flow change at each site, would describe the consequences for all items on their list. The lists were thus designed as memory guides. It was thought that the generic list for each discipline would initially be relevant to the river being considered, but might eventually, after use and adaptation with many rivers, become truly generic in that it could contain all aspects of that discipline that might be important in flow management of any river.

In this chapter, the nature and use of generic lists is described, and a first draft set of generic lists is proposed. It is hoped that these lists can be used and modified in future DRIFT applications, to become in time truly generic.

4.2 A brief outline of the history of generic lists

Brown & King (2000) defined a generic list as consisting of items of concern to each specialist that were expected to increase or decrease in some way (e.g. abundance, area, numeric value, concentration) as flow changed. The generic list thus comprised a list of ecosystem variables, such as an invertebrate species, a geomorphological feature or a chemical constituent. In DRIFT workshops, the consequence of any flow change would be described for each item on the list, using initially severity descriptions, and later severity ratings on a six-point scale from 0 (no change) to 6 (critically severe change) (Chapter 2). A generic-list item was chosen on the basis of its 'ecological or social significance', that is, its role in wider ecosystemic or social processes. To date the entries that have appeared on generic lists have included:

- individual species: e.g. *Baetis harrisoni*, *Labeo capensis*;
- biological communities: e.g. riffle invertebrate community, lowland river fish community;
- ecosystem processes: e.g. erosion, deposition, spawning, migration;
- habitats: e.g. pool, riffle, marginal vegetation, interstitial spaces, substratum.

(*note: some of the above – such as the processes – are no longer seen as appropriate generic-list items – see later explanation in text)*

Generic lists were first used in an EF workshop on the Palmiet River (Brown *et al.* 2000), and have subsequently been used in two more EFAs in southern Africa: the Lesotho Highlands Water Project and the Breede River Basin Study. Examples of entries in the first attempts at generic lists illustrate the mixture of species, chemical concentrations and processes (Table 4.1).

Table 4.1 Examples of entries in generic lists (King *et al.* 2003)

Discipline	**Generic list entry**	**Description of the links to flow and social relevance**
Geomorphology	Deposition of colloidal material	Minimum velocity for maintenance of movement of colloidal material in main channel = 0.05 $m\ s^{-1}$.
		Muddy areas are linked to loss of cobble habitat, increased algal growth, bogging of livestock, and gastric illnesses.
Water quality	Nutrient levels	Nutrient levels in pools increase under low flow conditions. Water in pools flushed by > Class II floods.
		High nutrients encourage algal growth, which is linked to increased incidence of diarrhoea in people and livestock, and loss of cobble habitat.
Vegetation	*Chenopodium album*	Found mostly in the wetbank vegetation zone, the width of which is reduced by a reduction in volume and variability of lowflows and in number of Class I floods. Abundance is affected by narrowing of the zone.
		Important source of firewood. Also used as a medicine.
Fish	Maluti Minnow	Inhabits quiet, shallow waters in rocky reaches with high water quality
		IUCN Red Data Book rare species. Restricted to the Highlands of Lesotho. Threatened with extinction.
Invertebrates	*Simulium nigritarse*	Filter feeder in slow, eutrophic water.
		Blood-sucking pest of poultry.

In the Lesotho reports, generic lists were presented in the form shown in Table 4.2 (Brown *et al.* 2000). The table was divided into three columns (1) Name of the item, (2) the ecological significance of the changes to the item, and (3) social significance of changes to the item.

Table 4.2 Generic list of water-quality sub-components, with a summary of their ecological and social significance (after Brown *et al.* 2000).

Sub-component	**Ecological significance**	**Social Significance**
Rapid Bio-Assessment (RBA)	RBA will be important for monitoring. In the DRIFT assessment, RBA scores in summer and winter are noted so as to give an idea of which values are linked to low-flow and high-flow seasons. Low RBA values can indicate low habitat quality rather than low water quality –e.g. IFR 6 at Seaka Bridge. This needs to be described and assessed.	RBA assessments can detect localised effects such as those caused by washing clothes at low flows.
Temperature	Temperature needs to be carefully considered where flows are produced by dam releases, as the depth of off-take will greatly affect temperature. Extreme temperature can cause mortality, and lower than normal temperatures affect breeding cycles and persistence of species.	Water might be cold to walk or swim in. Temperature will also affect the availability of fish species.
Dissolved oxygen	DO needs to be carefully considered when flows are produced by dam releases, as the depth of off-take will affect temperature. If algal blooms occur pools can become anaerobic - anaerobic conditions in pools will favour nutrient release. Low DO levels can cause fish kills and will affect macroinvertebrates.	
pH	pH seldom seemed to be flow related. If metal ion pollution ever became a problem (which is unlikely)- pH governs metal ion availability and therefore toxicity.	Although it is unlikely, fish and macro-invertebrates could be affected if metal ions reaches toxic levels.
Nutrient (Tot-P, Tot-N, SRP, NO3) and TSS variability	If the range of TSS and nutrient increases, this indicates that particular flow classes have the capacity to carry a particular nutrient/TSS load. Any particular flow event may or may not actually carry its potential load – this depends on the nutrient and sediment availability in the catchment. But as flow events increase in magnitude so the potential range increases, and loss of particular flow classes can mean a loss of particular ranges - and loss of variability. Loss of the range means loss of extreme carrying events, and loss of amounts of suspended material and nutrients.	A decrease in the range of TSS and nutrients means they have either not been transported at all, or have been deposited. If they are deposited at high flows, on features which subsequently are exposed at lower flows - they contribute to flood plain fertility, and can contribute to changes in geomorphology and therefore in habitat availability. If they are deposited in pools they cause filling-in, and act as "sinks" from which nutrients (and suspended material) can be released.

In the Breede River Basin Study EFA, for the first time, specialists entered workshop findings directly onto computer sheets. A system of codes was devised to allow easy and accurate entry of the specialists' inputs directly into DRIFT-SOLVER. To do this, the generic lists were separated into two types: a 'component' generic list and a 'specific' generic list, and each of these was filled in before the workshop as part of the starter document information. The specific generic list was much the same as the earlier ones, itemizing species or features of concern, each with its own code number, the ecological significance of each item, and its most obvious links to the flow regime (Table 4.3). The flow-category generic list (Table 4.4) consisted of general wisdoms on flow-related effects per discipline. For example, the general effects of declining wet-season low flows or dry-season low flows (column 2) on invertebrate assemblages were described (column 3), as well as the broader ecological implications of this (column 4). Each of these generic flow responses had a code number (column 1) to avoid the specialists having to write the same information many times as a range of flow changes were considered.

In summary, the two lists were designed to allow specialists to quickly identify an item of concern (Table 4.3), describe its predicted response for any posed flow change (Table 4.4), and enter these into the computer by merely entering codes. The data were entered in separate EXCEL files (Table 4.5) per discipline and site. Each file contained several worksheets, one for each flow category, indicating the item's response to changing wet-season low flows, dry-season low flows or the different classes of high flows. Entries in the table consisted of the appropriate flow-reduction level (column 1), the name and code of the item from the specific generic list (columns 2 and 3), the predicted general response to the flow reduction as a code (column 4), site and reduction-level specific comments (column 5), the direction, severity and likelihood of change (columns 6-8), and the quality of supporting data (column 9). The files from each member of the specialist team were collated to allow the overall consequences of each flow reduction to be evaluated.

A further adaptation of the generic lists was proposed by Arthington & Pusey (2003) to help them organise their knowledge and data as they completed DRIFT workshop documents. In their evaluation of the effects of changing flows on fish communities affected by the Lesotho Highlands Water Project, Arthington & Pusey, applying DRIFT, separated out the ecological requirements of fish (Table 4.6) from the consequences of flow reduction (Table 4.7). The generic tables listing the ecological requirements of fish were further separated into those likely to be affected by low flows (low flow issues) and high flows (high flow issues). Table 4.6 provides the 'high flow' list that included, amongst other factors, flood requirements for adult spawning cues; for maintenance of habitats for adult, juvenile and larval fish; for fish passage and dispersal; and for food production.

Their second generic list type (Table 4.7) summarised how changes in flow affect individual fish and fish populations in terms of change in condition; abundance (of adults, juveniles and larvae); spawning; or hatching success. The changes were rated in terms of the severity of impact on fish populations, from a change in fish health (least severe) to a loss of the species from the site (most severe).

A 'fish consequences summary' table (Table 4.8) was generated from these lists, which summarised the predicted consequences of each reduction in a flow category. The ecological requirements of fish that were expected to be impacted by the flow reduction (the 'issue codes' from Table 4.6) were entered into column 1 and the types of effects ('effect code' from Table 4.7) into column 3. The direction of change (increase or decrease in fish numbers), the severity (rated on a scale of 0 – 5 from no change in species abundance to loss of a species) and confidence in the above predictions were entered into column 4. The preferred seasonal timing of the remaining floods was recorded, as were the wider social consequences (not shown here). The ecosystem significance rating in row 6 of the headers to Table 4.8 refers to the ecosystem significance rating (1996 IUCN Red list rating) of the species being evaluated.

The various tables illustrate a number of activities and thought processes employed as specialists grapple with organizing their data and knowledge to predict the consequences of flow changes. The earliest concept of the generic list merely provided them with the entry point into complex considerations of how each item on the list could be affected by a range of other variables as flow changes. Some of the later generic lists do not meet the initial criteria for DRIFT generic lists in that they do not contain items that could increase or decrease in abundance (or area etc.). Instead, they are different kinds of lists, designed to create order in the complex considerations of flow change-ecosystem response (e.g. Arthington & Pusey., 2003). A possible development trend for the future that seems reflected here could be as follows.

- Level One: initial simple use of lists as memory guides.
- Level Two: an interim expert system with some degree of structure on linkages between lists for different disciplines. The structure could possibly take the form of items on generic lists linked by processes that could cause them to change in abundance. For example, an increase in the abundance of sand (Sedimentology generic list item), due to a flow change, could lead to a *process* of sedimentation, which in turn could cause a reduction in interstitial spaces (Geomorphology generic list item). This leads to a *process* of habitat change, causing a decreased abundance in the riffle-dwelling species assemblage (Macro-invertebrate generic-list item). Such logic pathways could be recorded, to allow re-assessment as knowledge increases.
- Level Three: an ultimate complex link of lists/disciplines in a kind of holistic model that predicts how the whole ecosystem could react to flow changes.

Some international research has already taken place, funded by the Worldfish Center, Cairo, on the potential for using Bayesian networks to guide data entry into DRIFT-SOLVER (Arthington & Pusey 2003). Other work is ongoing, on developing conceptual models of flow-ecosystem relationships for use with DRIFT generic lists (A. Arthington, Griffith University, Brisbane, pers. comm.), and streamlining the build-up of information from discipline to discipline in DRIFT applications (C. Brown, Southern Waters Ecological Research and Consulting, Cape Town, pers. comm.). These activities will essentially feed into Levels Two and possibly Three above, which are complex and will take time to develop. In this chapter, we address Level One, and a first draft set of generic lists.

4.3 The hierarchy within generic lists

Generic lists seem to be most useful if they each relate to a specific discipline. Discipline topics such as geomorphology, water quality, vegetation, fish and aquatic invertebrates are thus seen as the highest level in the generic-list hierarchy, and are here termed components (Figure 4.1). Within these components, sub-components consist of the main and most useful sub-groupings identified, just as flow categories are a useful way of sub-dividing the daily flow regime (Chapters 2 and 3). Thus, riparian vegetation can be grouped into a number of zones that occur with increasing elevation above the riverbed: aquatic, wet bank, lower dynamic, tree and shrub, upper dynamic (Boucher 2002). Each of these zones is a sub-component.

Items within sub-components are called elements. This level holds individual item(s) selected to represent the sub-component, and whose abundance (or area or concentration) can be measured. Typical elements might be a species or a chemical variable. The final level of the hierarchy is the sub-element, which is the finest breakdown of detail on the item being measured. If the element is a species, its sub-elements could be seeds, flowers and fruits (plant) or egg, larva, pupa and adult (animal).

Depending on their knowledge and the questions being asked, specialists can work at any level in the hierarchy from sub-component to sub-element, describing how that level would change with flow changes. If they start at the sub-element level, the changes will be summarized at the element level (e.g. if a certain flow change would reduce larval abundance but not affect eggs, what would be the overall impact on the species?).

Entries into the DRIFT database are at the **element** level, and so all predictions are summarised to this level. Further summaries, to the sub-component and component levels, are done automatically within the DRIFT database as weighted arithmetic summations. All representative elements are summarised in terms of the impact on the sub-component as a whole (e.g. if plant species X is predicted to decrease in abundance with a severity rating of 2 and plant species Y with a severity rating of 3, what is the overall predicted severity of change for vegetation zone Z as a whole?). Uncertainty is expressed by widening the range of severity ratings (e.g. a change with a severity rating of 2 indicates a higher level of confidence in the prediction than a severity rating of 2-4).

If the specialist does not have this level of understanding of the system, a prediction at the sub-component level can be made (e.g. Vegetation Zone Z will reduce in area with a severity of 2), with the automated link between element and sub-component in the DRIFT database over-written.

4.4. The draft generic lists

It is intended that one generic list should be created per relevant discipline, with the lists being modified in an ongoing exercise as DRIFT applications in different kinds of rivers reveal new needed items. From these (probably) long lists, specialists will select the items of relevance for each study site – possibly eventually selecting from drop-down lists in DRIFT software.

The main disciplines in DRIFT assessments, and thus the main candidates as components are:

- sedimentology
- fluvial geomorphology
- water chemistry and temperature
- vegetation
- aquatic macro-invertebrates
- fish.

Other optional components, used for rivers where they are identified as important are:

- microbiota
- plankton
- herpetofauna
- semi-aquatic mammals
- water birds
- terrestrial wildlife.

Sub-components for the six major components, and elements and sub-elements where appropriate, are suggested in Tables 4.9 – 4.14.

Figure 4.1 **Representation of the hierarchical organisation of generic lists, showing the structure of the riparian vegetation (a) and invertebrate (b) components in detail.** Not all the major components are shown. Dashed lines represent incomplete hierarchies.

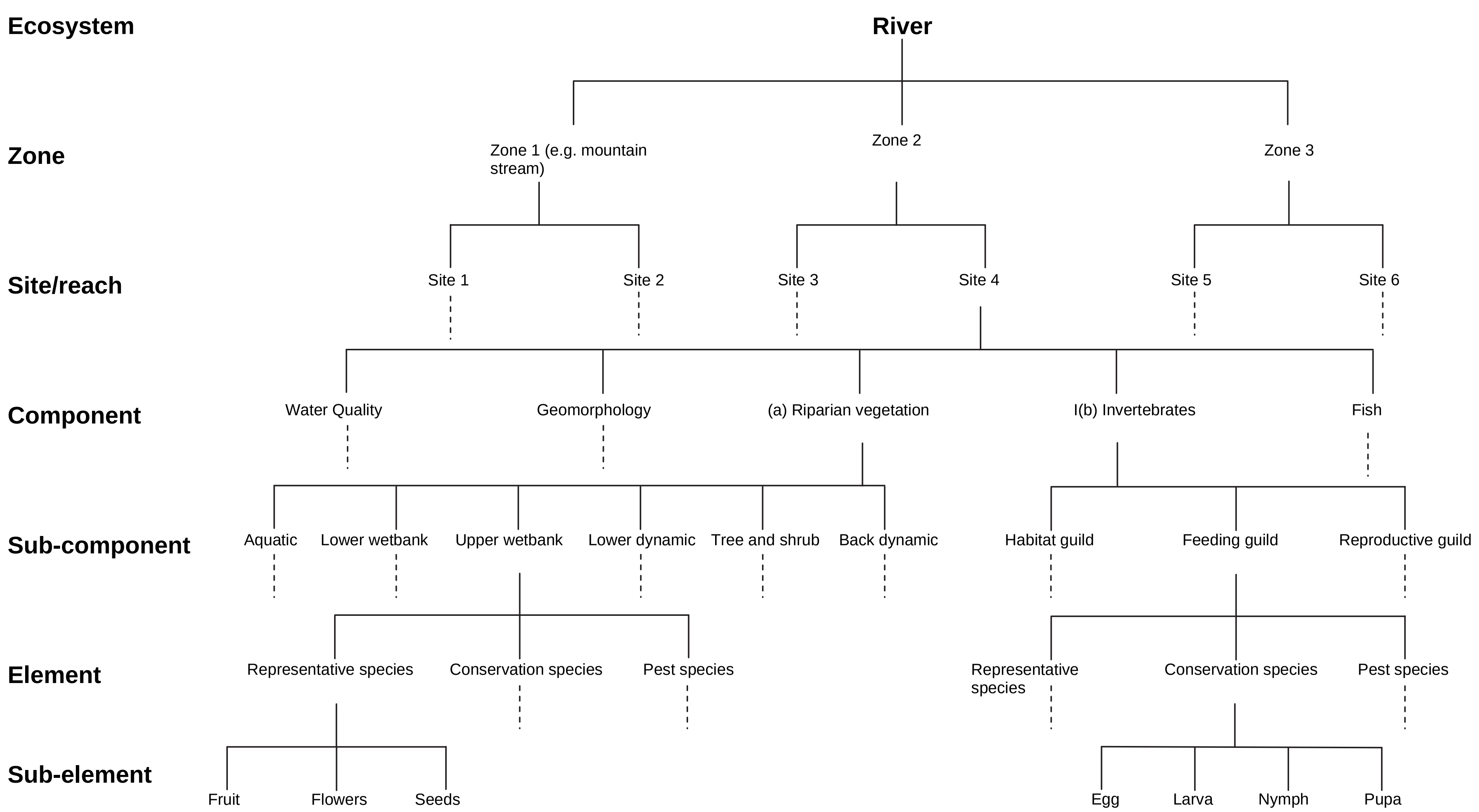

Table 4.3 Examples of entries in a DRIFT specific generic list from the Breede River Basin Study (after King *et al.* 2002c).

Code	Key taxa	Ecological significance	Most important aspects of the flow regime
MS1	*Baetis harrisoni*	These are deposit (collector gatherer) feeding species and will actively graze and feed on algal and diatomaceous growths on substrata. *B harrisoni* is the most tolerant of all mayflies to pollution. Loss of these species will result in more algal and diatom growth on stones and will cause these substrata to become slippery. Also bacteria, Oligochaetes and other invertebrates will colonise these modified substrata.	Occupy a wide range of physical and chemical conditions.
MS2	Hydropsychidae	These construct nets to filter particles from the current (plant and animal) and are occasional predators. Play a major role in energy transfer in rivers (high biomass). Form a diet for fish and waterfowl. Important as predators of blackfly larvae -– control numbers.	Transport of particulate organic matter for food.

Table 4.4 Examples of entries in a DRIFT flow category generic list: effects of different parts of the hydrological flow regime on macroinvertebrate assemblage structure from the Breede River Basin Study Study (after King *et al.* 2002c).

Code	Flow change	Effect on macroinvertebrate assemblage	Broader implications of changes to macroinvertebrate assemblage.
M1	Effect of declining wet-season lowflows.	If flows are constantly reduced then the dispersal of those species, dependant on adequate flow discharge and velocity to maintain colonising capacity (downstream drift), will be diminished and other species will start becoming more abundant and dominant.	
M2	Effect of declining dry-season lowflows.	Reduction in downstream drift (see M1). Reduced turbulence leading to reduced oxygen concentrations and predominance of taxa adapted to these conditions (Chironimidae, Tubificids).	Loss of sensitive riffle species, particularly grazers such as Baetidae, which control algal and diatom growth on the surface of rocks as well as collectors and filterers. Increase in proportion of short-lived opportunistic species such as Chironimidae and some Simuliidae.

Table 4.5. Examples of entries into the DRIFT-SOLVER spreadsheet for one component (invertebrates) at one site (Molenaars River), from the Breede River Basin Study (after King *et al.* 2002c).

FLOW REDUCTION: Level 1, 2, 3 or 4	**Specific generic code**	**Specific generic item**	**Flow reduction codes**	**Site-specific and reduction-specific comments**	**Dir (+/-)**	**Range of severity of change**	**Likelihood**	**Supporting data**
1	MS31	Riffle dwelling community	M25	Blephariceridae occurring in the riffles: indicator taxon for winter community. Maintenance of velocities between 0.6->1.0 $m.s^{-1}$ and minimum depth at 0.2 m in riffles	neg	1	high	high
2	MS31	Riffle dwelling community	M25	Blephariceridae occurring in the riffles: indicator taxon for winter community. Maintenance of velocities between 0.6->1.0 $m.s^{-1}$ and minimum depth at 0.2 m in riffles	neg	2-3	high	medium
3	MS31	Riffle dwelling community	M25	Blephariceridae occurring in the riffles: indicator taxon for winter community. Maintenance of velocities between 0.6->1.0 $m.s^{-1}$ and minimum depth at 0.2 m in riffles	neg	2-3	medium	medium

Table 4.6 Ecological requirements of fish likely to be affected as intra- and inter-annual floods are progressively removed from the flow regime (Arthington & Pusey 2003).

Issue code	High flow issues
1	Provision of spawning cues (discharge and water temperature)
2	Provision of migration cues for adult fish
3	Provision of cues for longitudinal and lateral dispersal of juveniles
4	Flushing of fish eggs and larvae
5	Access to lateral habitats for adults, juveniles and larvae
6	a) Availability of spawning habitat b) Quality of spawning habitat
7	Maintenance of interstitial spaces utilised by fish
8	Maintenance of tributary bars as spawning and larval habitat
9	Maintenance of depth in pools
10	Mobilization of coarse substrates
11	Maintenance of macro-channel and habitat diversity
12	Maintenance of the functional significance of riparian vegetation
13	Maintenance of aquatic invertebrate food supplies
14	Maintenance of allochthonous food supplies (terrestrial insects, fruit, flowers etc)
15	Maintenance of nutrient inputs and primary productivity

Table 4.7 Effects of flow regime change on fish individuals, populations and species interactions (Arthington & Pusey 2003).

Effect code	Effect on fish
A	Change in fish health (due to effects of disease, parasites, toxic algae, etc.)
B	Change in fish body condition (size, weight)
C	Change in abundances of <u>adult</u> fish
D	Change in abundance of <u>juvenile</u> fish
E	Change in abundance of <u>larval</u> fish
F	Change in spawning and hatching success
G	Change in level of passage and dispersal for: i) <u>Adults</u> ii) <u>Juveniles</u> iii) <u>Larvae</u>
H	Change in predation level
I	Change in competitive pressure
J	Change in mortality levels
K	Loss of species from site

Table 4.8 Fish consequence summary for the Design Limitation scenario in the Lesotho study (number of Class I intra-annual floods reduced from 6 to 3 per annum). Species codes: Smy = small-mouth yellowfish, Lmy = large-mouth yellowfish, Orm = Orange River mudfish (Arthington & Pusey 2003)

Study site number: 2		**Site name**: Katse	
Intra-annual floods: Class 1		**Component**: Fish	**Specialists**: AA, JR, MK
Flow scenario:			Design Limitation
Discharge range for scenario and component:			15.9 – 48 $m^3 s^{-1}$
Flood reduction level for scenario:			from 6 to 3 Class I floods
Ecosystem significance rating:			5*
Generic List of ecological issues affecting fish at site			
Issue	**Species**	**Explanation of consequences**	**Ratings**
1, 2, 3, 4, 5, 6, 7, 9, 13	Rock catfish*	A, B, D, E, Preferred seasonal timing of floods: Oct. - March Social III	Direction: -ve Quantity/severity: 2-3 Confidence: medium
1, 2, 3, 4, 5, 6, 7, 9, 13	Smy Lmy*	A, B, D, E, Preferred seasonal timing of floods: Oct. - March Social III	Direction: -ve Quantity/Severity: 2-3 Confidence: medium
1, 2, 3, 4, 5, 6, 7, 9, 13	Orm	D-F Preferred seasonal timing of floods: Oct. - March Social O	Direction: 0 Quantity/Severity: 1 Confidence: medium
1, 2, 3, 4, 5, 6, 7, 9, 13	Trout	B-F Preferred seasonal timing of floods: May – Sept. Social IV	Direction: -ve Quantity/Severity: 3-4 Confidence: medium

Example of interpretation of entries:
Ecosystem Significance Rating: 5* (rock catfish, largemouth yellowfish are Red Data species).
Issue 4 = Flushing of fish eggs and larvae
D = Change in abundance of juvenile fish.
Direction: -ve = decrease in abundance of all species at site as the number of Class I floods is reduced from 6 to 3.
Preferred seasonal timing of Class I intra-annual floods: Oct. – March (spawning season for all fish except trout). Trout spawn from May to September in Lesotho rivers.
Quantity/Severity 4-5 = Very few ecological requirements met, severe change in species abundance expected.

Table 4.9 Generic list of sub-components, elements and sub-elements for the component *sediments*.

Component	Sub-component	Element	Sub-element
Sediments	Fines	Colloids	
		Silt/mud	
	Sand	Fine sand	
		Coarse sand	
	Gravel	Fine gravel	
		Coarse gravel	
	Cobble	Small cobble	
		Large cobble	
	Boulder	Small boulder	
		Large boulder	
	Bedrock	Smooth	
		Fractured	
	Mean particle size		
	Biofilm on rocks		
	Embeddedness of coarse material in fines and sand		

Table 4.10 Generic list of sub-components, elements and sub-elements for the specialist field of *channel form* (after Rowntree & Wadeson 1999).

Component	Sub-component (morphological units)	Element (hydraulic biotopes)	Sub-element
Channel form – alluvial channels	Pool	Backwater Slackwater Pool Glide Chute Run Riffle Rapid Cascade Waterfall Boil	Flow types: • Free fall • Cascade • Broken standing waves • Undular standing waves • Fast riffle • Slow riffle • Rippled surface • Smooth boundary turbulent • Barely perceptible flow • No flow
Channel form – alluvial channels	Backwater		
Channel form – alluvial channels	Rip channel		
Channel form – alluvial channels	Plane bed		
Channel form – alluvial channels	Lateral bar or channel side bar		
Channel form – alluvial channels	Bar		
Channel form – alluvial channels	Step		
Channel form – alluvial channels	Rapid		
Channel form – alluvial channels	Riffle		
Channel form – alluvial channels	Bench		
Channel form – alluvial channels	Island		
Channel form - bedrock channels	Pool		
Channel form - bedrock channels	Backwater		
Channel form - bedrock channels	Waterfall		
Channel form - bedrock channels	Cataract		
Channel form - bedrock channels	Rapid		
Channel form - bedrock channels	Bedrock pavement		
Channel form - bedrock channels	Bedrock core bar		

Table 4.11 Generic list of sub-components, elements and sub-elements for the specialist field of *water quality and temperature* (after DWAF 1996).

Component	Sub-component	Element	Sub-element
Water chemistry and temperature	System variables	Temperature	Mean Maximum Minimum Range Diel variation
		pH	
		Dissolved oxygen – conc./ % saturatn	
	Non-toxic inorganic constituents	Total suspended solids /turbidity/water clarity	Concentration of individual named ion or inorganic salt e.g. Na_2SO_4
		Total dissolved solids /conductivity/salinity	
	Nutrients	Phosphates	concentration of ortho-phosphate
			concentration of total P
		Nitrogen	Concentration of nitrate or nitrite
			Total nitrogen
			Concentration of ammonia/ammonium
	Toxins and pollutants	Enter name	Concentration
	Response variables	Phytoplankton/periphyton	Concentration of Chl a

Table 4.12 Generic list of sub-components, elements and sub-elements for the specialist field of *vegetation* (Boucher 2002).

Component	Sub-component	Element	Sub-element
Vegetation	Aquatic	• Representative species • Conservation species • Pest species	Fruit
	lower wetbank		
	upper wetbank		Flowers
	lower dynamic		
	tree and shrub		Seeds
	back dynamic		

Table 4.13 Generic list of sub-components, elements and sub-elements for the specialist field of *aquatic macro-invertebrates*.

Component	Sub-component	Element	Sub-element
Macro-invertebrates	*Feeding guild* • shredder • collector-gatherer • collectpr-filterer • Scraper • Predator *Habitat guild* • Pool assemblage • Riffle assemblage • Run assemblage • Floodplain assemblage • Vegetation assemblage • Backwater assemblage *Reproducutive guild* • Univoltine • Multivoltine • Other	• Representative species • Conservation species • Pest species	• Egg • Larva • Pupa • Nymph • Adult

Table 4.14 Generic list of sub-components, elements and sub-elements for the specialist field of *fish*.

Component	Sub-component	Element	Sub-element
Fish	*Reproductive guild (habitat)* • Lithophil • Pelagophil • Phytophil • Psammophil *Reproductive guild (behavioural)* • Guarding • Non-guarding • Scatterer • Hider • Nest builder • Bearer (external or internal) *Feeding guild* • Benthivore • Insectivore**Error! Not a valid link.** • Planktivore • Piscivore • Herbivore • Detritivore • Omnivore *Reproductive strategy* • Iteroparous • Semelparous • Total spawner • Serial spawner *Movement* • Migratory • Residential	• Representative species • Conservation species • Pest species	• Egg • Larva • Juvenile • Adult

4.5 Conclusion

Generic lists guide the entry of consequence data into the DRIFT database, and could also impart structure to specialist inputs to flow assessments where other methodologies are used. If the lists are amended with use and found to become truly generic, then they could guide the next stage of development – the linkage of generic lists with relevant processes (Development Level 2 in Section 4.2).

As an additional example, the following generic list could be used to guide predictions of the effects on subsistence users of river resources changing as a result of flow changes.

Table 4.15 Generic list of sub-components, elements and sub-elements for the specialist field of *subsistence resource use*.

Component	Sub-component	Element	Sub-element
Subsistence use	Community health	Skin and eyes	
		Internal parasites	
		External parasites	
		Malaria	
		Schistosomiasis	
		Anthrax	
		Nutritional deficiency	
		Viral infection	
		Bacterial infection	
		Diarrhoea	
	Livestock health	Internal parasite	
		External parasite	
		Bacterial infection	
		Viral infection	
		Nutritional deficiency	
		Grazing (toxic plants)	
		Physical (bogging)	
	Water supply		
	Fish		
	Firewood		
	Construction material		
	Medicinal herbs		
	Wild vegetables		
	Quality of life		
	Crossing river		
	Washing clothes		
	Tourism and biodivesity	IUCN Red Data species	
	Culture and recreation	Baptism	
		Swimming	

5. A REVIEW OF THE IMPACTS OF LARGE DAMS ON SUBSISTENCE USERS OF DOWNSTREAM AQUATIC ECOSYSTEMS AND THE METHODS CURRENTLY USED TO QUANTIFY THEM

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5.1 Introduction

5.1.1 Environmental flows

Balancing the utilisation (development) of aquatic ecosystems for various human needs and the protection of these ecosystems, so that they can continue to be used by present and future generations, is one of the central challenges in water-resource management. Environmental flows are increasingly being recognized as a valuable tool in water-resource management as they provide the manager with an indication of the volume and timing of water required to maintain a river ecosystem in some pre-determined condition.

An Environmental Flow (EF) can be defined as: "water that is purposefully left in or released into an aquatic ecosystem to maintain it in a condition that will support its direct and indirect use values" (King *et al.* 2000b). EFs are based on an understanding of how flow changes can cause changes in river condition. This understanding can be used to describe flows for the river that will:

- minimise or mitigate against the downstream impacts of a water-resource development;
- rehabilitate systems impacted by past developments;
- allow calculation of the costs of compensating people downstream for such impacts.

Ideally, the decision on the condition in which an ecosystem is to be maintained should be guided by a Public Participation Process (PPP) (King *et al*. 2000b). In order for people to conclude what that future condition should be, they need to be able to weigh up the different options available to them. In general, the closer to natural the desired condition of the aquatic system, the greater the volume of the original flow regime that will be required as an environmental flow. In other words, the more natural the desired state for an ecosystem, the less water will be available for other uses, such as abstraction for cities or agriculture (Brown & King 2002a).

5.1.2 Environmental flows assessments

The creation of options, or scenarios, that link a required volume of water (and the distribution of that water in time) to an expected river condition is usually done as part of an Environmental Flow Assessment (EFA). An EFA can be defined as a synthesis of data on, and understanding of, a river ecosystem in order to provide scenarios of the impacts of changes in flow. In its most comprehensive form it provides a structured assessment of the consequences of different levels of water abstraction or other flow manipulations on all biophysical components of an ecosystem, such as the channel, the quality of the water, and the plants and animals. Increasingly in developing countries, these assessments also incorporate the consequences of flow manipulation for rural people who live alongside and who *directly utilise* the resources offered by the river, such as water for drinking, food (fish and vegetables) and reeds (Metsi Consultants 2000e).

EFAs provide information for decision-makers on flow options to mitigate the potential impacts of water-resource developments on rivers in two main ways.

1. They illustrate the levels of mitigation that can be achieved by reserving different volumes of water for river maintenance, including the most appropriate distribution of the reserved volume. For instance, the EFA would stipulate the magnitude, duration and frequency of the floods required in a river to maintain banks and floodplains, or of small floods to stimulate fish spawning. Similarly, an EFA could provide the timing and size of a flood needed to breach an estuary mouth, and the possible consequence of that flood not being provided.
2. The more advanced EFAs define in detail the water quality, physical habitat and biotic characteristics that typify the desired condition of the river, and the flow regime most likely to achieve this. In this manner, EFAs define measurables that can be used for management of the resource.

Useful global reviews of EFA methodologies are provided by Tharme (1996) and Dunbar *et al*. (1998). The methodologies vary widely in their data requirements and in the level of detail they provide. A group of methodologies, known collectively as Holistic Methodologies (Arthington *et al*. 1992), have emerged in South Africa and Australia as a favoured approach for EFAs. Holistic approaches are essentially ways of organising and using flow-related data and knowledge from different disciplines, and often incorporate a variety of discipline specific methods, such as fish models that can predict likely population trends with changing flows. As such they are better described as *methodologies*, which implies the linking of several distinct procedures or methods (Trihey and Stalnaker 1985) to produce an output that none could have produced alone.

Two of these holistic methodologies, both from South Africa, include explicit reference to the inclusion of sociological data in the flow-assessment process. The Building Block Methodology (BBM) (King *et al.* 2000a) and DRIFT (an acronym for *Downstream Response to Instream Flow Transformations*) (King *et al*. 2003), formally incorporate subsistence-use modules that aim to identify the likely impacts of different levels of flow manipulation on downstream rural populations (Brown & King 2000).

Considerable research has gone into the development or adaptation of biophysical methods that can be used within an holistic approach. Relatively little has been done to develop or adapt methods that can predict the consequences for subsistence users of flow related changes in the ecosystems on which they depend. The authors of both DRIFT and the BBM recognise that further development of their social components is necessary, in order to formalise the interaction between biophysical and sociological specialists on the EFA team, and to quantify the social impacts of a changing river.

5.1.3 Focus on large dams

Much of the research on the sociological implications of water-resource developments has concentrated on the impacts of large dams, and so this forms a major focus in this review. Other types of water resource-developments are not intentionally excluded, but are far more rarely or poorly reported on. All of the EF methods and principles discussed are probably applicable regardless of the nature of the upstream water resource development(s).

5.1.4 Aims of the review

In this chapter, international literature is reviewed on the impacts of flow-related changes to river ecosystems on human communities making direct subsistence use of the river's resources. Particular emphasis is placed on the methods used in these assessments.

5.2 Large dams and their impacts on aquatic ecosystems

5.2.1 Large dams: definition and purpose

A large dam is defined as having either:

- a wall height of greater or equal to 15 m (McCully 1996) or;
- a reservoir capacity of greater than 3×10^6 m^3 (Baur & Rudolph 2001).

Large dams are built primarily to provide (Agyeman 2001):

- hydroelectric power;
- water for irrigation;
- storage for flood alleviation;
- domestic and industrial water supplies for urban areas.

Often these benefits are obtained at the cost of downstream changes in the targeted river and to sections of society making direct use of that environment (Goldsmith & Hildyard 1984; McCully 1996; WCD 2000).

5.2.2 Locations of large dams

Current world trends suggest that the majority of recently built or proposed large dams are in developing countries (Table 5.1; Lerer & Scudder 1999). They are located mostly in rural areas, and often in upland regions.

Table 5.1 Estimated annual investment in dams in the 1990s in $US billion per year (data from WCD 2000).

Type of dams	**Developing Countries**	**Developed Countries**	**Total**
Dams for hydropower	12-18	7-10	19-28
Dams for irrigation	8-11		
Dams for water supply	1.5	3-5	13-18
Dams for flood control	0.5-1.0		
Total	**22-31**	**10-15**	**32-46**

This emphasis on developing countries has resulted in any upstream and downstream impacts of large dams being experienced mainly by rural riparian communities, many of which might use the rivers for subsistence (McCully 1996; WCD 2000). Communities in developed countries have also been affected (Berkes 1988), but not often directly through loss of food and other river resources. In developing countries, rural communities are often the most marginalised members of society with very little or no income (Derman & Poultney 1987; McCully 1996) and river resources might be a vital component of their livelihoods.

5.2.3 Effects of large dams on aquatic ecosystems

The effects of large dams on aquatic ecosystems have been reviewed extensively (Table 5.2; Ward & Stanford 1979; de Moor 1986; McCully 1996; Beilfuss *et al.* 2002). For instance, Brown & King (2002a) state that a large dam(s) in the upper reaches of a river, with poor or no downstream releases, may cause one or more of the following: a decline in water quality (e.g. Kafue River, Zambia); the erosion and collapse of river banks, deltas and coastlines (e.g. Nile River, Egypt) (McNeill 2000; McManus 2002); loss of agricultural land (e.g. Senegal River, Senegal) (Adams 2000a); collapse of a river fishery (e.g. lower Zambezi River, Mozambique) (Beilfuss *et al.* 2002); decline of an important estuarine wetland (e.g. Berg River, South Africa), or the decline of a marine fishery dependent on that estuary as a nursery area for juvenile fish (e.g. Senegal River) (Kloff & Pieterse 2002). Most of these environmental impacts had direct or indirect socio-economic costs.

It is clear from Table 5.2 that the impacts of large dams on aquatic ecosystems are not limited to the inundated upstream reaches and those immediately downstream of the dam wall. Regulation of flows and sediments in one part of a river can affect parts of the river tens or even hundreds of kilometres downstream. Furthermore, many of these impacts evolve slowly over years or even decades, and so may be difficult to link directly to a specific water-resource development (Brown & King 2002a). As such, there has been little impetus until recently to include downstream social and ecological costs in the cost-benefit analyses of large dams proposals.

5.3 Impacts of dams on downstream subsistence communities

5.3.1 Introduction

In many cases, perceptions of impacts by communities will differ from those of the development agencies (Berkes 1988).

Certain social impacts resulting from the construction of large dams are well documented and well understood. Most of these, however, relate to the relocation of communities living in the upstream area likely to be inundated. These upstream impacts are by no means insignificant (Goldsmith & Hildyard 1984; McCully 1996; Lerer & Scudder 1999; Sandler *et al.*2000), and include:

- loss of homes;
- loss of ancestral grounds;
- loss of resources such as fishing and hunting grounds as well as other riparian resources;
- loss of cropping lands;
- loss of grazing lands;
- loss of area for eco-tourism;
- health problems during and post construction of the dam;
- far-reaching lifestyle changes.

Table 5.2 Typical changes in a river downstream of a large dam (modified from Bergkamp *et al.* 2000).

Ecosystem Feature	Impact
Daily, seasonal and annual flows	Changes in flow could reduce: • flow variability • flood peaks • low-flow levels • overbank flooding and floodplain inundation • groundwater recharge
Sediment dynamics	Changes in sediment flows could: • alter morphology of the channel, floodplain and coastal delta • alter water turbidity • degrade the channel near the dam due to erosion • increase sedimentation further downstream
Floodplain	• loss of connectivity with river • loss of fertile fine suspended solids • vegetation encroachment
Coastal Deltas	• Increased erosion of coastal deltas as a result of a sediment inputy

For the most part, little attention has been paid to communities living downstream of dams (Adams 2000). In many cases, these communities are considered to be outside of the "zone of impact" of the dam, and are excluded from the planning stages of projects (Shoemaker 1998) despite considerable evidence that dam-related impacts on aquatic ecosystems can be experienced many hundreds of kilometers downstream of the dam wall. In the case of the Yali Falls Dam in Cambodia, the Swiss construction company Electowatt Co. Ltd, considered the "zone of impact" downstream of the dam to be eight km (Fisheries Office 2000), yet a subsequent study recorded dam-related impacts on communities 200 km downstream of the dam site (Fisheries Office 2000). Similarly, the construction of High Aswan Dam in Egypt led to the decline of sardine and shrimp fisheries in the Nile Delta, some 1200 km downstream of the dam, which had employed 30,000 people (McNeill 2000). These stocks have since recovered to almost pre-Aswan levels, but primarily as a result of food provided by the organic effluents entering the river from Cairo (P. Dugan, Worldfish Center, Egypt, pers.comm.).

5.3.2 Impacts of flow changes on downstream subsistence users of aquatic ecosystems

Most of the literature on downstream impacts of dams concentrates on tangible losses, such as loss of resources and the resultant impacts on the economies and livelihoods of communities. Intangible impacts, such as aesthetic issues, quality-of-life issues, and loss of, or damage to, cultural sites or recreational areas are not often considered (Box 5.1).

Box 5.1 Summary list of potential intangible impacts of the Lesotho Highlands Water Project (Metsi Consultants 2002a)

- Loss of fitness-for-use of the rivers by sangomas and traditional healers for healing and cleansing rituals in the river.
- Loss of fitness-for-use of the rivers for cultural purposes, such as baptism or initiation.
- Reduced aesthetic value of scenic rivers with high potential for tourism.
- Loss of unimpacted rivers that represent African high-elevation headwaters.
- Loss of biodiversity.
- Loss of rare, endangered or unknown species.
- Reduction in the role of the river in controlling movements of livestock.
- Increased ease of river crossing by people.
- The mythical river snake is angered by an unhealthy river with unnaturally low flows.
- Loss of, or impact on, leisure opportunities such as: swimming, running, fighting and horse riding along and in the river, enjoying natural landscapes. Rural dwellers find the rivers very beautiful, especially during floods.
- Limitation of future development options in the catchment (option values), through loss of water and degradation in water quality.
- Channel changes where tributaries join the main river.
- Loss or reduction of ecological processes such as production of nutrients and purification of poor-quality water.
- Reduced bequest value (e.g. leaving unspoilt riverine ecosystems for future generations to use) or existence value, (e.g. knowing that wild scenic places exist for their own sake).

Some studies of the impacts of flow transformation on downstream resource users do exist and have produced or predicted the following impacts – some tangible, some intangible:

- loss of riparian floodplains, resulting in a reduction in:
- fish abundances (McCully 1996; Shoemaker 1998; Fearnside 1999; Adams 2000; Agyeman 2001; Beilfuss 2001);
- subsistence agriculture (Fisheries Office 2001; Beilfuss 2002; Metsi Consultants 2002a);
- loss of wild vegetables and herbs (Fisheries Office 2000; Beilfuss 2002), and resultant illnesses related to the loss of essential trace elements (Metsi Consultants 2002a);
- reduction in coastal fisheries (McCully 1996; Davies & Day 1998; Fearnside 1999);
- increase in water borne parasitic diseases such as malaria, schistosomiasis, onchocerciasis (Salem-Murdoc & Niasse 1993; McCully 1996);
- proliferation of pest species (de Moor 1986);
- increased flooding and unseasonal flood events (Goldsmith & Hildyard 1984; McCully 1996; Davies & Day 1998; Fisheries Office 2000);
- reduction in the quality of drinking water (Heeg & Breen 1982; Horowitz et *al.* 1991; Fisheries Office 2000; Malan & Day 2002);
- salinisation of freshwater in arid areas (Goldsmith & Hildyard 1984; McCully 1996; Hoffman & Ashwell 2001);
- erosion of river banks and coastlines (McCully 1996; Davies & Day 1998);
- destruction of archaeological information (Tim Hart, UCT Archaeology Department pers. comm. 2002);
- reduction of wildlife (Fisheries Office 2000);
- loss of fuelwood (Beilfuss 2002, Metsi Consultants 2002a);
- increase in livestock injuries (Davies & Day 1998; Beilfuss 2002, Metsi Consultants 2002a);
- algal blooms (Fisheries Office 2000);
- reduction in materials used for building (Fisheries Office 2000, Metsi Consultants 2002a);
- transportation problems (Shoemaker 1998; Fisheries Office 2000; Metsi Consultants 2002a).

Each of these impacts can have a knock-on effect on community values, way of life, traditions or health profiles. For instance, a reduction in fish catches could lead to a migration of traditional fishers from communities as they search for work elsewhere (Adams 2000b).

Aquatic resources

Fish

A major recorded impact of dams is the downstream reduction in or loss of fish as a resource to riparian communities (McCully 1996; Shoemaker 1998; Fearnside 1999; Adams 2000b; Agyeman 2001; Beilfuss 2001). For many rural riparian communities, particularly in developing countries where nutrition is frequently compromised, fish are an important protein source (Heeg & Breen 1982; Scudder & Conelly 1984 in Horowitz et *al.* 1991; Adams 2000b; Beilfuss et *al.*

2002), and loss of fish resources can have a significant negative impact on their nutritional status (Jackson & Marmulla 2001; Metsi Consultants 2002a). Fishing is also central to the way of life in many areas, and its loss can result in a loss of community identity and traditions (Jackson & Marmulla 2001; Box 5.2).

Box 5.2 A field report on the socio-economic and environmental effects of the Nam Theun-Hinboun Hydropower Dam (Shoemaker 1998)

The following are quotes from fisher people living downstream of the dam site.

"I buy directly from the village fisherman. They come to the riverbank by the bridge every morning. This year in the dry season there are very few fish. They no longer come down since the dam was closed… I estimate that there is a 70% reduction in the number of Nam Kading fish available for sale here compared to this time last year. Restaurant owner, Pat Kading, 1998.

"In the past we caught enough fish to eat and to sell for cash income. In fact, fish from the Nam Kading were usually sold to Vientiane because of their good taste, better that Nam Ngum fish. Now we can only catch enough to eat but not to sell in the market. One problem is the (human) population has increased making fishing more difficult. But since the dam closure the situation has become much worse." Fisherman, Bay Phosay, 1998.

"The villages of Hat Sai Kham, Phongam, Pak Soum and Phisay all depend on fishing in the Nam Kading. In all these villages the fishing is now difficult. Fish catches have been reduced by 50 or 70%." Women selling fish at the small market at Ban Phosay, 1998.

Fish are dependent on patterns in a natural flow regime that trigger their breeding and migrations, provide havens for juveniles and maintain habitats. Dams alter these patterns: unseasonal releases from dams can flush eggs and juveniles from the system; attenuation of highflow events can reduce floodplain inundation, preventing fish from accessing their breeding areas on the floodplain (Welcomme 2001; Davies & Day 1998); and unnaturally low flows disrupt the connectivity of the system, creating barriers to migration. Changes in water quality also affect fish numbers and diversity (Miranda 2001).

Post-dam surveys clearly illustrate their effect on downstream fish abundances and dependent human communities. Since 1970, when Egypt's Aswan Dam came into operation, the number of fish species on the Nile River has dropped by nearly two thirds and the sardine catch in the Mediterranean Sea has dropped by nearly 80% (McCully 1996). After the Pak Mun Dam was built in the 1990s on Thailand's Mun River, the 150 fish species that once inhabited the river virtually disappeared (World Resources Institute 1998/99). Hoguane (1997) studied the effect of Zambezi River management on the prawn fishery of central Mozambique, establishing that prawn abundance is directly related to runoff patterns in the Zambezi River. The presence and operation of Cahora Bassa Dam on the Zambezi has resulted in a loss of these prawn fisheries estimated at

$10-20 million per annum. Following the construction of the Manantali Dam in the Middle Senegal River Valley, some downstream villages reported complete elimination of the fish harvests as a result of reduction in flows. Other villages reported a reduction in catch size, fish size and an absence of certain species (Salem-Murdock & Niasse 1993). Downstream of the Kainji Dam in Nigeria, fish yields in the Niger River dropped from 19.6 tons to 12.2 tons between 1967, before, and 1969, after, the closure of the dam (Davies 1979 in Horowitz *et al.* 1991). The pre-impact environmental flow study for the Lesotho Highlands Water Project predicted an annual loss of 10 000 kg per annum of fish if the original Treaty level releases were implemented (Metsi Consultants 2002a), and downstream of the Yali Falls Dam in Vietnam, local communities reported a decline in all river fish species occurring in the river, with some species impacted more than others (Fisheries Office 2000).

In Canada (McCully 1996), parts of South America and in the Arctic (Adams 2000b), fish harvests have also been affected by high concentrations of mercury in fish in and downstream of impoundments. Although not directly related to flow changes in the downstream river, these elevated mercury levels were a consequence of the reservoir inundating terrestrial ecosystems. Inorganic mercury occurs in many soils, but the filled reservoirs contained bacteria feeding on rotting matter that transform inorganic mercury to methyl mercury, which is toxic to humans. This was then absorbed into the food chain and, via fish, potentially by humans.

Other instream resources

Other instream resources frequently used by rural communities and commonly affected by instream dams are:

- building sand (e.g. Heeg & Breen 1982; Metsi Consultants 2000e);
- aquatic macrophytes;
- drinking water for domestic use and livestock (Metsi Consultants 2000e; Fisheries Office 2000);
- frogs (CRES 2001);
- shellfish (Fisheries Office 2000);
- turtles (CRES 2001).

Riparian resources

Wild vegetables

Most studies reported a loss of wild vegetables and plants used by communities as a source of nutrition. The losses were attributed to reductions in flows, particularly floods (Fisheries Office 2001; Beilfuss *et al.* 2002; Metsi Consultants 2002a). For instance, villagers below the Yali Falls Dam reported the post-dam loss of 14 types of riverine plants that had previously been used as a food source (Fisheries Office 2000).

Fuelwood

In mountainous areas where woody vegetation is restricted to the river margins, changes in flooding regimes can affect the number of trees and shrubs, and hence impact on the availability of wood used in cooking and heating. Predicted loss of fuelwood was a major component of the forecasted costs associated with flow changes downstream of the LHWP dams (Metsi Consultants 2002a). With the building of the upland Manantali Hydroelectric Dam on the Senegal River, a 120-km^2 forest used for, *inter alia*, firewood and building materials, was severely impacted when the groundwater underlying it was depleted. Dam releases that would have helped to replenish the groundwater were promised but not implemented (Kloff & Pieterse 2002).

Not all riparian people depend on rivers for wood. Beilfuss *et al.* (2002), studying the impacts of hydrological change on subsistence productions systems in the lower Zambezi River Valley, observed that wood was harvested from the hillsides rather than the riparian zone and that there was no evidence that changes in flows had impacted on fuelwood availability. He noted, however, that harvest pressure on non-riparian trees and shrubs increased when food was short or crops failed, and that these episodes were linked to flood patterns in the Zambezi River that had been affected by Cahora Bassa Dam.

Medicinal plants

Bielfuss *et al.* (2002) reported that although changes in flooding patterns affected the availability of various fruits and plants in the lower Zambezi River valley, Mozambique, there was very little impact on medicinal plants because these were mostly collected from the terrestrial landscape rather than floodplains. In contrast, traditional healers in the Thukela River valley, South Africa, rely heavily on wild plant resources growing alongside the river, some of which are found only in the riparian zone (Huggins *et al.* 2002). Metsi Consultants (2002a) predicted that changes in flows downstream of the LHWP dams, in particular a reduction in floods, would have a negative effect on the availability of some medicinal plants. Other studies make reference to negative impacts on plants collected by communities, some of which are presumably used for medicinal purposes (Fisheries Office 2000).

Building materials

Many rural communities utilise various natural resources such as wood, sand and mud, as building materials for their homes. Loss of these resources from riparian zones as a consequence of flow changes has been recorded in, *inter alia*, the Pongola Floodplain (Heeg & Breen 1982), the lower Zambezi valley (Beilfuss *et al*. 2002) and the Malibamatsô River (Metsi Consultants 2002a).

Wildlife

Subsistence hunting is a widespread and important source of food for rural communities. In the past, subsistence hunting in the Zambezi Delta was closely linked to flooding because the animals were drawn to the floodplains for water and grazing. Changes in the flood regime following the construction of Kariba and Cahora Bassa Dams impacted on hunting in two major ways (Beilfuss *et al.* 2002):

- the delta floodplain floods less frequently and as a consequence is less boggy and more easily accessible by vehicle, which has led to illegal over-hunting;

- reduced flooding has affected the grass on the floodplain, which has altered wildlife grazing patterns and reduced the carrying capacity of the area.

Anderson *et al.* (1990) and Chande & Dutton (1997) predicted that there could be a substantial economic return, in terms of trophy hunting and meat production, if healthy populations of Cape buffalo and other game species could be restored to the floodplain grasslands below the dam.

In Zambia, changes in flows caused by the Kafue Gorge and Itezhi-tezhi Dams on the Kafue River have been linked to a decline in the numbers of endemic Kafue lechwe (Mwanza 2001; McCartney *et al.* 2002). In addition, there have been changes in the communities of aquatic plants, invertebrates and fish, which have negatively impacted the bird population (McCartney *et al.* 2002). A survey of wattled crane in the region indicated that the population has dropped from 3000 in 1974 (Douthwaite 1974) to roughly 970 in 2001 (Kamwenshe & Beilfuss 2002).

Flow changes as a result of the Yali Falls Dam allegedly also impacted on wildlife downstream, and there are numerous records of unexplained deaths of wild mammals and some bird species (Fisheries Office 2000).

Water quality

Water quality downstream of dams is affected by chemical changes to the water as a result of impoundment, or changes as a result of alterations in the natural flow regime of the river. Both of these will impact on downstream people using the water.

Effects of impoundment on water quality can include, depending on the level of release of the reservoir water (US EPA 1995):

- reduced sediments;
- decreased concentrations of dissolved oxygen;
- altered temperature regimes;
- increased levels of nutrients;
- increased levels of some pollutants, such as mercury, hydrogen sulphide and manganese.

Even if the water in the impoundment is of good quality, flow changes downstream of the dam can result in poor quality water in the river. A reduction in dilution and flushing of debris such as trees, branches or dead animals, can result in the water becoming badly contaminated and unusable (CRES 2001). In some cases flow reduction means that downstream aquifers are not adequately replenished, which impacts on the yield and quality of potable water obtained from shallow wells. As a result people travel further to collect water or draw it directly from the river, which can have detrimental effects on their health (Horowitz *et al.* 1991).

Algal blooms

Research from Australia and elsewhere indicates that managed flows in rivers are a major factor influencing cyanobacteria bloom formation (Croke 2002). Cyanobacteria, commonly known as blue-green algae, occur in small quantities in most aquatic environments (Harding & Paxton

2001). In healthy systems that is not a problem, but with unnaturally low flows and warm water temperatures, cyanobacteria can out-compete other algae and proliferate to pest proportions.

Some species of cyanobacteria develop powerful biological toxins (Harding & Paxton 2001), which can pose a serious threat to the health of humans and animals (Davies & Day 1998; Whittington 1999; Harding & Paxton 2001; Blanch 2002). Fatalities in domestic and stock animals from ingesting these have been recorded globally, with recent human fatalities also reported from South America (Harding & Paxton 2001). In 1991, a major cyanobacterial bloom, attributed to the excessive regulation of flows for irrigation occurred along a 1000-km stretch of the Darling River in the Murray-Darling Basin, Australia (Blanch 2002). Communities along the Darling River are dependant on the river for domestic drinking water and for stock watering (Whittington 1999), and had to have water trucked in.

Reports in Cambodia of deteriorating water quality in the Se San River downstream of the Yali Falls Dam were first reported in 1996, after a major release of water from the dam. Downstream riparian people reported serious health problems after drinking the water, including (Fisheries Office 2000):

- stomach aches;
- diarrhoea;
- respiratory problems;
- throat and nose irritation;
- dizziness;
- vomiting;
- coughing.

It was suggested that toxic blue-green algae had proliferated in the reservoir (Fisheries Office 2000), but there were no available water-quality records.

Salinisation

Irregular flows after dam construction can also result in salinisation in downstream reaches, particularly in arid areas, as flushing of salts may be reduced (Davies & Day 1998; Newman & Goss 2000). Irrigation return flows often exacerbate this effect. In many parts of the world, this has resulted in downstream water quality being managed through dam releases, as in the Breede River, South Africa (Brown & Fowler 2000). Salinity problems in the Murray-Darling Basin are not limited to the arid areas of the basin (River Darling), but also occur in the River Murray in South Australia (River Murray Catchment Water Management Board 2001). As waters become more saline they are less suitable for drinking and irrigation and can have a great negative impact on crop yields.

Evaporation of water from the surface of reservoirs of impoundments can also increase the salinity of downstream rivers. Such evaporation from Hoover Dam (Lake Mead) and Glen Canyon Dam (Lake Powel) are said to have increased the salinity of the Colorado River in the U.S.A. by 100 mg l^{-1} relative to pre-impoundment levels (Goldsmith & Hildyard 1984). The evaporation rate at the reservoir of the High Aswan Dam in Egypt has led to a ten percent increase in salinity in the downstream Nile River, with water entering the reservoir with a salinity of about 200 parts per million (ppm) and being released downstream at the dam at about 220 ppm (Goldsmith & Hildyard 1984).

A reduction in the volume (and thus force) of water discharging from a river to the sea can also lead to the upstream intrusion of saltwater (Middleton 1999). The High Aswan Dam on the Nile River has resulted in saltwater intruding 50 km further upstream than recorded before the dam (McNeill 2000). Similar impacts have been recorded in Mozambique, where the downstream and estuarine sections of the Incomati, Limpopo, Buzi and Pungwe Rivers are affected by saltwater intrusion (Brown & King 2002a) as a result of water abstraction in South Africa, Swaziland and Zimbabwe. An increase in salinity downstream of Cahora Bassa Dam has threatened the mangrove swamps at the mouth of the Zambezi River, which are an important breeding ground for both shrimps and prawns (Middleton 1999).

Many sea fisheries worldwide are dependent on the volume and timing of freshwater discharges from rivers. Reductions in freshwater input, particularly flushing flows, results in increased salinities in estuaries, which has impacted negatively on fish production in the estuaries. Estuarine salinity levels in the Volga, Dniester, Dnieper and Don Rivers were estimated to have increased by *c.* 400 % between 1977 and 1987 (McCully 2001). These estuaries are nursery areas for many inshore fishes, and the increased salinities have reduced commercial fish catches in the Caspian, Black and Azov Seas by up to 98% (McCully 2001).

The Diama Dam at the mouth of the Senegal River, which was constructed to provide water for irrigation and to prevent seawater intrusion in the Senegal River during the dry season (Kloff & Pieterse 2002), effectively disrupted the ecosystem of the mouth. Prior to construction of the dam the delta varied between a near freshwater system in the wet season and a brackish system during the dry season, with salty water recorded up to 100 km upstream in drought years. The riparian communities historically made use of a number of riverine resources in the mouth area for their daily living needs, such as (Kloff & Pieterse 2002):

- *Acacia nilotica:* a hardwood termite-resistant tree used for building, firewood and charcoal;
- *Sporobolus robustus:* a perennial grass used along with leather for making mats that were an important source of income;
- *Nymphaea lotus:* a water lilly the seeds of which are a food source as well as being used for medicinal purposes.

After construction of the dam, the downstream ecosystem became hyper-saline, while that upstream became permanently fresh (Kloff & Pieterse 2002). The seasonally dry floodplain became a shallow freshwater lake. As a result *A. nilotica,* which used to fringe the river, and large fields of *S. robustus* and *N. lotus*, which used to occur in seasonal pools, were replaced by dense stands of *Typha australis* (Kloff & Pieterse 2002).

Agriculture

Sediments, seeds and nutrients carried on the floodwaters of rivers are carried by floodwaters onto floodplains. As a result riparian floodplains are among the most fertile, productive and diverse ecosystems in the world (Bergkamp *et al.* 2000).

Dams impact on floodplains in two main ways:

- by attenuating floods and reducing the flooding frequency of downstream floodplains;
- by trapping sediments that would otherwise have been deposited on the floodplains (Davies & Day 1998, Bergkamp *et al.* 2000).

Flood-recession farming on floodplains is practiced by riparian communities in many parts of the world (Smedley & Ribeiro-Tôrres 1979; Heeg & Breen 1982; Salem-Murdock & Niasse 1993; McCully 1996; Adams 2000a; Beilfuss *et al*. 2002), and is highly susceptible to either of the above impacts. Crops are planted before the flood season and harvested once the floodwaters have receded. It is believed that rice has been grown in Africa in this manner for the past 3000 years (McCully 1996). These farmers are often skilled in judging crops and soil selection in relation to the level reached by the flood waters (Adams 2000b, Beilfuss *et al.* 2002). Changes in the flooding regime can considerably reduce the crop options available to such farmers (Salem-Murdock & Niasse 1993), and nutrient-rich silt trapped in a reservoir is lost to downstream reaches (Goldsmith and Hildyard 1984, McCully 1996). While fertilisers can compensate for the loss of nutrients (McCully 1996), these are expensive and negatively impact on downstream water quality (Davies & Day 1998). The silts, which favour the growth of rooted plants on which productivity is often dependent (Heeg & Breen 1982), are irreplaceable.

The impacts of dams on subsistence farming are significant (Adams 2000a, Bielfuss 2002). In Nigeria, the Bakolori Dam on the Sokoto River considerably reduced peak flows, affecting the depth, duration and extent of inundation of the floodplains for up to 120 km downstream (Adams 1985). In three surveyed villages flooding frequency and extent of inundation were halved, and post-dam harvests were 18-50 % of those prior to the dam. In the lower Zambezi Valley downstream of Cahora Bassa Dam, farmers who previously practiced flood-recession farming were forced to establish croplands away from the river. The new croplands yielded only one harvest per annum, compared to two before the dam (Beilfuss *et al.* 2002). Flood-recession farming is still widespread on some of the unregulated tributaries of the Zambezi River (Beilfuss 2002).

As a direct result of reduced opportunities for flood-recession farming, farmers tend to move towards irrigated farming (Horowitz *et al.* 1991), where problems such as the following may manifest:

- salinisation (McNeill 2000);
- increased waterborne diseases, such as malaria, schistosomiasis and filariasis[1] (Goldsmith & Hildyard 1984, McCully 1996);

[1] Irrigation canals are prime breeding ground for the vectors that spread these diseases

- lifestyle changes, including (Salem-Murdock & Niasse 1993):
    - migration: with the shift from flood recession farming to irrigation, members of a community move away from their village to seek employment to finance the costs of irrigation farming;
    - a change in division of labour: many of the community members that migrate to seek outside employment are males, which leaves women to take over the traditionally male role of agricultural production.

Aseasonal and unexpected flood releases also affect agriculture downstream of dams. In 1989, after a natural flood had occurred and then receded, peasant farmers in the Senegal River valley planted flood-recession crops on the floodplain as they had done for generations. The operators of Manantali Dam then released another flood as part of their operating procedure, which drowned the seedlings in the low-lying areas. Many of the effected peasant farmers could not afford to replace the seeds (Horowitz & Salem-Murdock 1993, in Adams 2000a).

Impacts on food production and food security negatively affect the nutritional status of communities, leading to increased vulnerability to illness and diseases (Metsi Consultants 1999). In the Senegal River, malnutrition increased dramatically after interruption of the annual floods by Manantali Dam and a concurrent decline in both traditional agricultural practices and fish catches (World Resources Institute 1998/9).

Human health and safety

Health

Health issues, such as skin and dietary problems, were reported in all the studies reviewed on the downstream impacts of dams on people (Heeg & Breen 1982; CRES 2001; Fisheries Office 2000; Metsi Consultants 2002a; Table 5.3). Many villagers using the Malibamatso River downstream of Katse Dam in Lesotho reported the water as "too contaminated to be used safely as drinking water". Villagers also complained about skin rashes after crossing or swimming in the river. The poor water quality was said to be caused by the growth of algae (*bolele*), due to the reduced flow, and to small black aquatic insects *(thalaboliba, maphele, mankulunyane*), all of which were directly attributed to reduced flows since the dam (Metsi Consultants 1999). The health data revealed that for the 0-5 year age group, water-related diseases (gastro-enteritis, skin diseases and eye infections) accounted for 50% of the diseases diagnosed (Metsi Consultants 1999).

After the closure of Pongola Poort Dam in South Africa in 1979, there was an outbreak of typhoid in the communities on the downstream Pongola Floodplain. This was attributed to people drinking water obtained by digging in the bed of the non-flowing river (Heeg & Breen 1982).

Table 5.3 Examples of water-related infections with estimates of worldwide morbidity, mortality and the number of people currently affected (Metsi Consultants 1999).

Disease	Morbidity per annum	Mortality per annum	No. of people affected	Linked to flow changes?
Water-borne and water-washed diseases				
Cholera	**No figures available**			**Yes (Davies & Day 1998)**
Diarrhoeal diseases (e.g. salmonellosis, shigellosis, campylobacter, *E. coli*, rotavirus, amoebiasis and giardiasis)	>1 500 million episodes in children under 5 years	4 million in children under 5 years	> 2 000 million	Yes (Metsi Consultants 1999)
Enteric fevers (paratyphoid, typhoid)	1 million infections (1977-78)	25 000		Yes (Heeg & Breen 1982)
Poliomyelitis	204 000 infections (1990)	25 000		
Ascariasis (roundworm)	800-1 000 million cases	20 000		No (Davies & Day 1998)
Leptospirosis (Weil disease) Trichuriasis (whipworm)	No figures available No figures available			
Water-washed skin and eye infections				
Trachoma	6-9 million people blind		500 million	No (Davies & Day 1998)
Leishmaniasis	12 million infected; 400 000 new infections per year		350 million	No (McCully 2001)
Relapsing fever	No figures available			
Water-based				
Typhus fever (rickettsiosis)	No figures available			
Schistosomiasis (bilharzias)	200 million	200 000	500-600 million	Yes (Hunter *et al.* 1982)
Dracunculiasis (guinea worm)	>10 million		>100 million	
Water-related insect vectors				

African trypanosomiasis (sleeping sickness)	20 000 new cases annually		50 million	
Lymphatic filariasis	90 million		900 million	
Malaria	267 million	1-2 million	2 100 million	Yes (McCully 1996)
Onchocerciasis (river blindness)	18 million	20-50 x 10^3	85-90 million	Yes (Goldsmith & Hildyard 1984)
Yellow fever	10 000-25 000			
Dengue fever	30-60 million infected			Yes

Changes in flow volumes and patterns, particularly those associated with the construction of large dams, have been linked with an increase in vector-borne diseases such as malaria, schistosomiasis encephalitis, hemorrhagic fevers, gastroenterritis, internal parasites, filariasis and onchocerciasis (Goldsmith & Hildyard 1984, McCully 1996, Lerer & Scudder 1999, Beilfuss *et al.* 2002; Table 5.3). A malaria epidemic in 1942/43 in Upper Egypt attributed to an invasion of *Anopheles gambiae* from the Sudan as a consequence of water development caused 130 000 deaths. During June 1991 there was a major outbreak of malaria from Khartoum to Atbara on the Nile River. This was attributed to low flows in the river as a result of flow regulation through impoundment. Isolated pools created in the riverbed provided an ideal breeding habitat for *Anopheles arabiensis* the malaria vector found in the region (Jobin 1998). In Ghana, surveys for urinary schistosomiasis undertaken prior to the building of the Akosombo Dam in the 1960s found a low prevalence of the disease (5-10% in children) (Zakhary 1997). Within a year of the lake reaching its maximum level, prevalence of up to 90% was found in lakeside communities. Increased schistosomiasis prevalence following the construction of large dams has also been noted in Nigeria, Sudan and Mali (Hunter *et al.* 1982). With the water-development project on the Senegal River and the building of the upland Manantali hydroelectric dam, ecosystem changes in the river basin occurred. The net impact of the development on people’s health has thus far been negative, with schistosomiasis, diarrhoeal disease and malaria increasing, in some cases dramatically, in the area between the Manantali and Diama Dams (Jobin 1998). It has been estimated that the current annual death rate from malaria could be reduced by 30% if appropriate flows from the Manantali Dam were introduced (Malanes 2001).

Health problems also arise from the accidental swallowing or inhalation of algal blooms. Effects have ranged from mild (irritation of skin and mucosal membranes, sore eyes) to severe (skin blistering, stomatitis, and severe pulmonary consolidation). Severe gastro-enteritis, vomiting and liver-function impairment in populations supplied from water bodies dominated by blue-green algae have also been noted. There is also limited evidence of increased incidences of liver cancer in populations exposed to low concentrations of hepatotoxins in untreated water over an extended period (WRI undated).

Safety

The mistaken belief that, once a dam has been constructed, the river 'has been tamed' and can be controlled by the dam operators (Goldsmith & Hildyard 1984, McCully 1996, Davies & Day 1998) has resulted in communities that used to migrate seasonally between the flood plain and terrestrial lands settling semi-permanently on floodplains (Beilfuss 2001). This misconception is reinforced when no maintenance flood releases are made from the dam, because there could be many years when mid-range floods do not occur in the downstream river. A dam's ability to control flood events is dependent on numerous factors, including the size of the impoundment and the water levels in the impoundment at the time of a flood, but it is probably safe to say that no dam can control all floods that occur in a system. When large floods do occur in such rivers, they are thus potentially far more hazardous than in the un-dammed river.

The devastating effects of floods in the lower Zambezi River in early 2001 were exacerbated by releases from Kariba and Cahora Bassa Dams to avoid overtopping, and by the fact that people had established homes on the downstream floodplain. The combination resulted in a number of deaths and left thousands homeless (Beilfuss *et al.* 2002). In other areas, similar hazards have been reported from dam releases resulting in unexpected floods in the downstream river. In the Se San River, unseasonal artificial floods caused by releases from the Yali Falls Dam have resulted in deaths downstream in Cambodia, and the loss of dry-season gardens to an estimated 50% of the downstream families in Vietnam (Fisheries Office 2000). Fishermen who used to sleep on the sand bars and islands on the river during the dry season are no longer able to do so because of the unpredictability of the flow regime (Fisheries Office 2000). It would appear that the Vietnamese authorities inform Vietnamese villages downstream about the releases but not their Cambodian counterparts (Fisheries Office 2000).

Although flood control is one of the main reasons for building dams there are reports of dams increasing the frequency and severity of floods. On the Uruguay River, in Uruguay, flood risks increased downstream of the Salto Grande Dam as a result of hydropower releases, and some of the many inhabited islands in the downstream river have had to be abandoned (McCully 1996).

Livestock health and safety

Metsi Consultants (2002a) predicted an increase in vectors of livestock diseases downstream of LHWP dams and changes in a number of other factors:

- an increase in nuisance insects, such as blackflies;
- a reduction in grazing and browsing resources;
- an increase in dangerous areas where cattle could sink into mud.

The lowflows and lack of variability that characterise flow regimes downstream of many dams favour the development of Simuliidae (blackflies; de Moor 1986). Blackflies are blood-sucking pests of poultry and cattle. Their saliva contains anticoagulants to allow uninterrupted feeding. Animals severely attacked can abort foetuses, lose productivity and, in some cases, bleed to death (Robinson 1993; Davies & Day 1998).

Such predictions are supported by recorded deteriorations in the health and abundance of livestock in the lower Zambezi River, downstream of Kariba and Cahora Bassa Dams (Beilfuss *et al.* 2002). Stanley & Alpers (1975) also cite increases of diseases, such as river fluke, and changes in the distribution of trypanosomiasis, as a result of dams. Trypanosomiasis is transmitted by the tsetse-fly (*Trypanosoma congolense, T vivaz, or T. brucei*), which affects cattle, pigs, camels, goats, sheep and people. It is not clear if Stanley & Alpers (1975) felt the increase in disease was due to flow changes.

As is the case for humans, unseasonal and untimely floods present a risk to animals. Communities along the Se San River blame dam-induced flooding and poor water quality downstream of the Yali Falls Dam for substantial losses in livestock (Fisheries Office 2000), although the researchers reported that at that time diseases to livestock in the entire Ratanakiri Province had increased dramatically (Fisheries Office 2000).

Other effects

Erosion and aggradation

Sediments carried into an impoundment fall from suspension as the water slows. The water released through the dam wall thus carries an unnaturally low sediment load, and is termed "silt hungry". With distance from the dam, the suspended load increases to what is within the range of normal for the downstream modified flow regime, but it does this by eroding the channel along which it flows. If it has not reached this new equilibrium by the time it reaches the ocean, the coastline will be eroded (McCully 1996; Davies & Day 1998; Berkamp *et al.*2000). The effects of silt-depravation are usually most evident in river reaches immediately downstream of a dam, where in some cases all fine sediments are removed from the channel, leaving the bedrock exposed (Davies & Day 1998). Such armouring results in a loss of habitats for riverine biota, such as the gravel spawning beds used by many species of fish.

Erosion by silt-hungry water can be off-set (and complicated) by the reduction of flows, particularly middle-order high flows, downstream of a dam. The resultant loss of power to move sediments causes the deposition of sediments in areas where this may not have occurred previously. This can lead to a reduction in channel depth and a corresponding increase in channel width, and other changes in the direction of river flow, threatening riparian farming activities (McCully 1996, Berkamp *et al.* 2000) and dwellings in villages (Adams 2000b).

Reduced sediment loads also affect deltas, which are formed at the mouths of rivers when the sediments transported by the rivers are deposited there at a faster rate than the ocean currents can erode them (McManus 2002). Among other things, deltas are important breeding areas for fish and fertile agricultural regions. Reducing the downstream sediment load of a river results in less deposition at the mouth leading to enhanced erosion by the ocean currents and coastal retreat (Middleton 1999). For instance, it is estimated that the High Aswan Dam entraps 98 % of the Nile Rivers sediment load (McManus 2002), and as a result the Nile delta has shrunk significantly. In some places the coastline has retreated as much as 70-90 m a^{-1} (McNeill 2000), leading to a straightening of the coast line and damage to harbours (McManus 2002).

Disruption of transportation

The effect of flow regulation on transportation is to some extent dependent on the size of the river. For instance, in Lesotho where the rivers themselves are not used to facilitate transport but at times present an obstacle to travellers, river regulation may make river crossings safer (notwithstanding the unexpected flooding issues discussed above). By way of contrast, the Se San River is travelled extensively using dugout canoes (Fisheries Office 2000). There, unnatural flood releases from the upstream Yali Falls Dam have destroyed thousands of boats and several engines (Fisheries Office 2000). Low flows can also hamper river transport: *"Here we depend on the river for transport. This has become difficult with the low water level. We have fruit orchards across and up the river and we always used our boats to bring the fruit down to the village but now our boats get stuck. Now we will need a road."* --Villager, Ban Phongam, Theun River downstream of Yali Falls Dam, Laos, (Shoemaker 1998).

Loss of riverine archeological deposits

Observations downstream of Gariep Dam on the Orange River, South Africa, indicate that archaeological sites several hundred years old are being eroded away (T. Hart, UCT, pers. comm.). This has been attributed to reduction in silt loads in the river downstream of the dam, combined with new erosion gullies from the tributaries that were caused by reduced flows in the main channel (e.g. Thoms 1999).

5.4 Case studies highlighting methods used to evaluate or predict human impact as a result of flow changes

5.4.1 Introduction

Apart from their focus on socio-economic flow related impacts downstream of dams, most of the comprehensive studies reviewed in this section share one important feature; they were conducted *after construction of the dams had been completed.*

- The Institute for Development Anthropology (IDA) undertook a detailed study of the socioeconomic and environmental impacts in the Middle Senegal River Valley as result of the construction of the Manantali Dam on the Senegal River (Muneera & Madiodio 1993).
- The Fisheries Office of Ratanakiri Province in Cambodia (Fisheries Office 2000) and the Center for Natural Resources and Environmental Studies (CRES) of the Vietnam National University (CRES 2001) investigated the downstream socio-economic impacts of the Yali Falls Dam on the people living alongside the Se San River, a tributary of the Mekong River.

- In the Zambezi Wetlands Conservation Program (Beilfuss *et al.* 2002) undertook a study of the impact of hydrological changes on subsistence production systems and socio-cultural values in the Lower Zambezi Valley.
- A comprehensive socio-economic investigation, undertaken by Sechaba Consultants, which formed an integral part of the EFA for Lesotho, commenced after the completion of Phase 1a of the LHWP project, i.e. once Katse Dam was already in operation. Additionally, however, it considered potential downstream consequences of a dam and a weir still at the design stage as well as other planned dams (Metsi 2000g).

The dearth of pre-impact or predictive studies in this review is partly a reflection of the difficulty in obtaining planning documents and data, but also reflects the past neglect of downstream issues in dam planning activities. Commonly, no baseline data have been collected prior to dam construction, and predicted downstream social, environmental and financial impacts have not been important inputs to the decision-making process.

Although numerous socio-economic studies have been conducted prior to dam construction, most have concentrated on identifying upstream inundation effects, such as for Epupa Falls, Nambia (Corbett 2000), Bujagali Falls, Uganda (Talbot *et al.* 2001), Magugu Dam on the Komati River, Swaziland and the Pangue Dam on the Biobio River, Chile (Opaso 1999). Exceptions to this include downstream impact studies for the Sabie River (Pollard & Simanowitz 1997), the Lesotho Highlands Water Project (Metsi Consultants 2002a) and the recently begun study of the Thukela River (Huggins *et al.* 2002).

All of the studies reviewed used some version of Rapid Rural Appraisal (RRA; Evans 1997) or Participatory Rural Appraisal (PRA; Evans 1997). In general, (Evans 1997), RRA or PRA involves the collection of background data on a community prior to a series of visits to sample villages. During the village visits, time is structured to allow a variety of methods, such as household questionnaires, to be employed, for cross-checking the information gathered and for adapting methods where necessary.

5.4.2 Cambodia - Se San River downstream of Yali Falls Dam (1)

Objectives of the study

The study, by the Fisheries Office (2000), aimed to review the impacts on the livelihoods of communities living on the Se San River in the Ratanakiri Province of Cambodia downstream of the Yali Falls Dam.

Process

Planning phase
This consisted of:

- a literature review of hydropower schemes and their downstream effects, with particular emphasis on the Yali Falls Dam;
- preparation of a draft questionnaire, based on knowledge of local circumstances;
- review of, and agreement on, the questionnaire at a workshop held in the study area and attended by the study team and local government officials;
- selection of the interview team of 12 people (nine men and three women). The team included four people from the Se San River Basin, who were able to speak the dialects of study area.

In the initial stages of the study the survey team included as many local government officials and affected village communities as possible in their interviews.

Survey phase
Interviews were conducted at fifty-nine villages populated by nine different ethnic groups along the river downstream of the dam. The most downstream village was 200 km from the dam site. The entire study lasted 21 days in April and May 2000.

- Surveys were conducted on a gender basis, with women in the survey team interviewing women in the community and men interviewing men. The same questionnaire sheets were used for all interviews. A copy of the questionnaire is available in electronic format on: http://203.144.77.39/DOC/sesan_report.zip
- The questionnaire was reviewed and revised after the initial interviews.
- The team also collected anecdotal information about villagers who had moved away from the river due to hardships experienced after the construction of the dam. The emigrant villagers were not visited or interviewed.

Outputs

The Fisheries Office (2000) study compiled the following data sets:

- **General information on each village**
    - name of the village;
    - district in which the village is located;
    - date that the village was visited;
    - community that occupied the village;
    - total number of people resident in the village;
    - number of females and males resident in the village;
    - number of families resident in the village;
    - ethnic group of the village;
    - brief history of the village;
    - list of the participants involved in interviews.

- **Deaths (human and livestock) attributed to changes in flow**
    - people killed as a result of unnatural flooding and the village they lived in;
    - numbers of each kind of domestic animal killed as a result of unnatural flooding and the village they belonged to.
- **Damage to downstream agricultural systems attributed to changes in flow**
    - name of the affected village;
    - area and type of cultivated land inundated in each;
    - year and season in which flooding occurred;
    - numbers of families affected.
- **Loss of fishing gear and boats attributed to unusual hydrological conditions**
    - name of the affected village;
    - type of equipment and quantity lost or damaged;
    - number of paddle and motorised boats lost;
    - numbers of families affected;
    - Material losses other than agricultural or fishing equipment.
- **Indigenous knowledge about the Yali Falls Dam**
    - name of the village;
    - length of time residents have been aware of the existence of Yali Falls Dam;
    - whether the residents are given advanced warning of releases from the dam;
    - history of flooding patterns since the dam.
- **Residents' opinion of the Yali Falls Dam**
    - name of the village;
    - difficulty in obtaining an opinion on the impacts of the dam from villagers;
    - appeals from villagers regarding the dam impacts;
    - reports on impacts to villages in Stung Treng Province of the Yali Falls Dam.

A further document, based on the results of the study, estimated the monetary value of the impacts on livelihoods (McKenney 2001).

Results/Findings

The Fisheries Office (2000) reported that half of the approximately 28 000 people living in the 32 villages surveyed during their study were rural dwelling small scale farmers. These farmers were dependent on lowland rice cultivation, vegetable gardening, fishing, foraging and other river-based livelihood activities for survival. People from all of the communities surveyed reported unusual changes in the hydrology of the Se San River beginning around October/November 1996. Typically, the changes were unnatural flooding and large daily fluctuations of water levels. The fluctuations included powerful surges that resulted in the loss of human lives and livestock. Other reported downstream impacts as a result of the dam were water-quality problems that affected the health of humans and livestock. The hydrological changes had a negative impact on downstream agriculture, with damage reported to both dry-season and wet-season agricultural systems. Other impacts included a loss of wild vegetables, a decline in wildlife, a significant decline in the downstream fisheries, and a loss of fishing equipment.

Recommendations

- **Community-based recommendations**
    - The socio-economic and ecological impacts that have negatively impacted on downstream communities be addressed urgently.
    - The Viet Nam Government, and others involved in the construction of the Yali Falls Dam, compensate for the losses to downstream communities, including loss of life and livelihood.
    - The Yali Falls Dam be either decommissioned or the downstream impacts mitigated through, *inter alia*, releases which replicate natural flows.
    - Should mitigation not occur, compensation to downstream communities be provided on a continual basis.
    - No further dams be built on the Se San River.
    - Development agencies, such as the Asian Development Bank withdraw support for the proposed Se San 3 Dam (proposed for a location 20 km downstream of Yali Falls).
- **Recommended research**
    - A detailed water quality survey on the Se San River, concentrating on nitrogen and phosphorous, and including algal sampling to test for toxins of blue green algae.
    - Detailed studies on the implications for human and livestock health of the Yali Falls Dam.
    - A survey of dam-related impacts on communities on the Se San River in Stung Treng Province from the confluence with the Sre Pok River to the Mekong River, and in Vietnam.
    - Monitoring of erosion and deposition downstream of the dam to evaluate the risk of wet-season flooding, and other socio-economic and ecological issues related to sedimentation.
    - In-depth studies on fish and fisheries of the Se San River.
    - Studies on the impact of the dam on birds, wildlife and reptiles.

The Fisheries (2000) report is available on http://203.144.77.39/DOC/ntfpyali.pdf.

5.4.3 Cambodia - Se San River downstream of Yali Falls Dam (2)

Objectives of the study

The study by CRES had the following objectives:

- assess the impacts of the Yali Falls Dam on downstream villages;
- identify what, if any, compensation villages have received for impacts from Yali Falls Dam;

- ascertain solutions adopted by local people to survive or mitigate the impacts of the dam in terms of livelihood changes, and their recommendations.

Process

As with the Fisheries Office (2000) study, the CRES study (CRES 2001) involved community members in all aspects of the study, as follows.

- A study team consisting of three men and one woman from CRES, three translators and one person from the Provincial Department of Science Technology and Environment, which divided into three to conduct interviews.
- A questionnaire based approach, which targeted villages directly alongside the river, as well as some 1-3 kilometers away from it that they believed were also dependant on the river. In each village the following people were interviewed.
    - The headman, as it was perceived that he would able to provide detailed information on the functioning of the village.
    - A selection of households. Sixty-six households were interviewed, with men and women interviewed together. Men gave different answers than women to the same question, and women tended to remember more details than men.
- An assessment of the agro-ecosystems used by households and the community as a whole.
- Daily team review sessions.

Outputs

The CRES study generated much the same kinds of data as the previous study.

Results/Findings

As did the Fisheries Office (2000) report, the CRES study (2001) study reported cases of unnatural flooding through releases from the Yali Falls dam. The CRES (2001) report indicated that these unnatural hydrological events resulted in a severe damages to: crops, livestock, household possessions, boats and rafts as well as fishing equipment. The dam also resulted in negative impacts on downstream fisheries, which were an important source of protein to villages. Since the construction of the dam there has been a noticeable decrease in fish catches. Some aquatic animals, such as soft shelled turtles, have disappeared from some areas completely. Where no releases were made from the dam, low-flow conditions downstream resulted in the loss of habitat for a number of fish, shrimp and crustacean species. These species normally feed on, amongst other things, malaria-carrying mosquito larvae, which increased in abundance with a concomitant increase in the incidence of malaria amongst downstream villages. In addition, the CRES (2001) reported that since the construction of the dam there have been negative changes to downstream water-quality, with negative effects on the health of the downstream villagers. As a result of the rapid fluctuations in flow, villagers have had to change fishing patterns, no longer sleeping in boats on the river while fishing but now in huts that had to be built some 10-15 m from the water's edge.

Recommendations

The following were recommended:

- additional studies on the impacts of the Yali Falls Dam on the environment, focussing on water and biological resources, biodiversity and farming;
- adequate mitigation procedures for relocated communities, including income generation, land for cultivation, and access to fresh water and firewood;
- compensation for flood losses to downstream villages.

The CRES (2001) report is available on http://www.irn.org/programs/vietnam/yali-e.pdf.

5.4.4 Mozambique - the Zambezi River downstream of Cahora Bassa Dam

Objectives

During 2000 and 2001, researchers and students from the University of Eduardo Mondlane, Mozambique, collected more than 750 hours of oral-history interviews from a selection of communities between Cahora Bassa Dam and the Zambezi Delta (Beilfuss *et al.* 2002). The aim was to describe the economic and cultural importance of pre-dam flooding for the riparian people of the Lower Zambezi, and compare these findings with the current production and social systems of those communities.

Process

An RRA process was used to conduct the interviews in the Lower Zambezi Valley. Interviews were conducted over a two-year period by three study teams. More than 700 interviews were held, targetting the following groups of people:

- village elders;
- traditional chiefs and headmen;
- secretaries;
- teachers;
- peasants;
- fisherman;
- hunters.

Interviewees were men and women over 50 years old who had lived next to the Zambezi River either:

- all of their lives;
- since prior to 1975; or
- at least the past five years.

All interviews were conducted in public, either within the grounds of the village, along the river, or at other key sites, and were participatory. The questionnaires encouraged narratives without the people being unduly influenced by the questions asked, and interviewees were allowed to discuss their particular issues of interest.

All interviews were recorded and later transcribed to English (northbank) and Portuguese and English (southbank). A follow-up meeting to discuss first-year results was held in March 2001, and a final meeting to review survey findings in November 2001.

The study team also facilitated a series of stakeholder meetings aimed at promoting dialogue on future flow releases from Cahora Bassa Dam (Beilfuss *et al.* 2002):

- in November 2000, a meeting was held between President Chissano of Mozambique, members of his cabinet and the Chiefs from the Zambezi Delta, where the impacts that hydrological changes on socio-economic activities and village life in the Zambezi Delta region were discussed;
- in 2001 and 2002 a series of meetings between decision-makers and stakeholders, including local communities and hydropower customers, was held to discuss a consensual approach to integrated management of the Zambezi basin.

Results/Findings

The findings of Beilfuss *et. al.* (2002) were as follows.

- There is an overwhelming perception amongst the population of the lower Zambezi valley that the upstream dams have radically changed the flood regime of the Zambezi River.
- Since construction of the upstream dams, the Zambezi River has changed from an annual flood regime of one major flood to one of erratic floods that can occur at any time. Historically, floods occurred between January and April followed by a dry season. Many socio-economic activities were linked to the timing of these floods. Currently, an irregular flood regime exists in which floods can occur in any month of the year. These hydrological changes have profoundly impacted the agricultural practices in the lower Zambezi Valley.
- Peasant farmers used to grow a variety of floodplain crops on the floodplains, guided by the mosaic of soil types with differing levels of fertility. As a result of the irregular flooding regime caused by the dams, the farmers have been forced to cultivate their crops on the uplands far away from the river, where they are now dependent on the annual rains to irrigate their crops.
- Water-resource projects in the lower Zambezi Valley have also impacted the following:
    - fisheries
    - wildlife
    - fruits and plants for food as well as medicine
    - water supply

- fuelwood
- building material
- livestock
- health.

It is believed that these impacts are not only of local concern but also of national importance to the economy of Mozambique.

Outputs

This study is still in progress and the final report is not yet available.

5.4.5 Senegal - Senegal River downstream of the Manantali Dam

Objectives

Unlike the previous studies, the Senegal River Basin Monitoring Activity (SRBMA) study was a comprehensive four-year investigation of riverine agricultural production systems downstream of the Manantali Dam in the Senegal River basin. The study aimed to evaluate the impacts of the changes in the flow regime in the Senegal River as a result of the Manantali Dam on downstream production systems, and was divided into two distinct phases (IDA 1993). The basic unit of analysis was the production space exploited by a village, or group of historically connected villages, and these production spaces were used to select study villages.

SRBMA I

The pilot phase, SRBMA I, focused on three Halpulaar villages in Matam, which represented the three integrated production zones of the region: riverine, recessional, and agro-silvo pastoral. Secondary villages were selected in areas with significant socio-economic, political and historical relationships with the primary villages. Data were collected qualitatively and quantitatively, using such techniques as formal and informal, individual, group, and community interviews; participant observation; life histories; and structured surveys and questionnaires carried out at regular intervals: weekly, biweekly, monthly, bimonthly, or seasonally.

Data were collected on the following:

- household consumption of different types of food such as grains, meat, fish, locally grown vegetables, and non-farm foods;
- production of crops using different types of agricultural lands;
- labour allocation to different agricultural practices including crop production and herding;
- land tenure;
- revenues generated by and expenditures on:
    - farm income;

- sale of livestock;
- sale of fish, firewood, personal effects and foodstuff;
- non-farming activities, such as those of artisans, tailors, bakers butchers, drivers, herders, marabouts (holy men) and healers;
- wages and salaries from the government and the private sector;
- rental of property and equipment;
- remittances;
- pensions.

The discussions and questionnaires covered issues related to all the main components of the production system: waalo, *falo* (agricultural recession lands located on riverbanks), jeeri (rain-fed agricultural land), irrigation, fishing, herding, petty commerce, and labor migration.

The results of SRBMA I were used to further the team's understanding of the floodplain and irrigation production systems, and to assist them in developing the more detailed, systematic approach required in SRBMA II (Horowitz *et al.* 1991).

SRBMA II

SRBMA II covered a wider geographic area than SRBMA I, and was more systematic in its approach. The understanding of the heterogeneity of farming households developed in SRBMA I was essential. The goal was to determine how Senegal Middle Valley households make use of scarce resources, respond to perceived opportunities and deal with perceived obstacles.

Nine production areas were selected, each of which was exploited by a group of historically connected villages. In total, some 331 households in 32 villages were incorporated into the study. In each, the relative proportions of floodplain (recession cultivation, herding, fishing) and irrigation activities were assessed and their comparative productivity in terms of land, labour, and capital determined. To the extent possible, household production goals and labour strategies were also determined.

Five types of relationships between floodplain cultivation and irrigation existed in the area:

- predominance or sole presence of floodplain cultivation;
- domination of floodplain cultivation over irrigation;
- relative balance between floodplain cultivation and irrigation;
- domination of irrigation over floodplain cultivation;
- predominance or sole presence of irrigation.

The configuration of these relationships within a particular area and household varied temporally and spatially according to factors such as the extent of the inundated plain (which declines from east to west), the presence of irrigated perimeters (more are present on the Ile à Morphil and in western Podor), rainfall patterns, flood patterns, household production goals, and differential access to resources.

Outputs

SRBMA I and II generated substantial quantitative data on agricultural production systems, which could be used to evaluate the impacts of changes as a result of changes in flooding regimes, including:

- the distribution of the different types of agricultural fields, and their use by different social groups;
- a detailed, gender- and age-specific analysis of agricultural and non-agricultural labour;
- the return on the factors of production; land, labour and capital;
- an analysis of use of animal and machine labour in the different production systems;
- nett yields and revenues generated per hectare for the different production systems;
- average annual total per capita household consumption;
- an analysis of household income (amount and sources).

The SRBMA II report analysed the reaction of communities living in the Middle Senegal River to the hydrological conditions of the Senegal River for 1990 and 1991, both of which were drought years, and made some recommendations on the equitable management of the Manantali Dam (Salem-Murdock and Niasse 1993).

Results/Findings

The study by the Institute for Development and Anthropology (IDA) of the Senegal River Valley produced the following findings (Horowitz *et. al.* 1991; IDA working Paper No. 55 (SRBMA I); Salem-Murdock & Niasse 1993; IDA working paper No. 94 (SRBMA II).

- The floodplain of the Senegal River was customarily used for a number of activities including floodplain recession farming, fishing and herding.
- These activities allowed residents of the Senegal River valley to exploit the wetland ecosystem during much of the year, providing an extensive network for exchange of grain, fish and dairy products.
- The loss of the natural flood regime and the predicted move from recession floodplain farming to that of irrigation farming as a result of this would lead to the loss of this productive use of the floodplain.
- An estimation of the market value derived per hectare from the primary products of the floodplain – sorghum, fish and livestock – indicated that this surpassed the value of rice production in the irrigated perimeters.

Other findings of the IDA study were that changes in the flow regime would impact on the following.

- *Acacia nilitica*, which is used for fuelwood and building material. The species is dependant on periodic flooding for regeneration.
- The annual flood of the Senegal River is an important driver in regeneration of the fisheries of the system.

- Groundwater recharge is dependant on surface runoff and the seasonal floods.
- Termination of flooding in the Senegal Valley will result in a reduction in production options available to communities. This could lead to an increase in human conflict as competition for dwindling resources increases.
- A change from flood-recession farming to irrigation farming would see a migration of community members from the region.
- As a result of migration of male members of the community from the region, there would be a change in the gender division of labour.

The conclusion of the IDA study was that it would make strong economic and environmental sense to sustain the existing downstream production patterns in way that would be compatible and not competitive with hydoelectrical power and irrigated agricultural needs.

Other recommendations

Further recommendations included (Salem-Murdock & Niasse 1993):

- multidisciplinary, collaborative research by social and physical scientists in the Senegal River Basin to document the environmental and socio-economic changes occurring in the river valley as a result of the Manantali Dam;
- inventorisation and monitoring of the flora and fauna of the Senegal Valley;
- seasonal monitoring of fish in the main river channel and on the floodplain.

5.4.6 Lesotho: Social Component of the EFA for Phase 1 of the Lesotho Highlands Water Project

Objectives

The study aimed to:

- identify those components of the riverine ecosystem used by the downstream population at risk (PAR);
- identify those utilised components of the riverine ecosystem that would be affected by reduced flows;
- quantify these in terms of loss or gain for a range of possible future flow regimes in order to enable their costing by the economist;
- identify mitigation and compensation measures for the resources lost;
- develop a strategy and framework that would lead to a mitigation and compensation policy for downstream reaches;
- initiate consultations with the communities living along the downstream reaches in order to solicit their input in the development of mitigation and compensation strategies.

Process

The LHWP social-impacts study had two stages: a pilot study and a socio-economic survey. The pilot study was conducted to establish which villages used the rivers and would be impacted by reductions in flows if the dams were built. It was also used to gain a first estimate of changes in flows would effect these villages both economically and socially. The second stage socio-economic survey established population figures, and quantified riverine resources used by communities within affected villages. Details are provided below.

The Pilot Study

Identification and quantification of the PAR was done through structured and open-ended interviews with individuals and small groups. The basic unit of study was defined as the household interview, and the logistical and legal (tribal law) constraints that dictated use of the resources associated with the study rivers ascertained. This information was then used to determine a corridor of resource use on either side of the study rivers, based on parameters such as (Metsi 2000g):

- distance from the river;
- topography, in particular gradient and thus accessibility of the river;
- nature of the river;
- presence of infrastructure, such as roads or bridges;
- culture, mentality and customs;
- forms of livelihood practiced;
- tribal laws limiting the use of some resources.

A corridor 5 km wide on either side of each river was recognised as containing communities with close links to the rivers. The demographics of the PAR within these corridors were obtained from national census data, and the location of relevant villages mapped. The pilot study also identified the river resources that the PAR used, including identification to species for all plants and animals. The interview sheet was supplemented by additional PRA methods such as (Metsi 2000g):

- elite interviews with specialists;
- two types of river-transect walks;
- completion of river-utilisation maps;
- river profiles;
- river utilisation calendars;
- photography.

<u>The detailed socio-economic study</u>

On the basis of results obtained from the pilot study, the detailed socio-economic survey encompassed three key activities in order to capture the complexity of river use:

- house hold interviews (HHI);
- specific river user interviews (SRUI);

- chief interviews (CI).

<u>Interviews with House Holds (HHI)</u> The findings, needs and concerns of a wide range of disciplines in the EFA had to be integrated in the HHI. Hence, the development, testing and refinement of the questionnaires used in the HHI were time consuming. The final version contained seven sections and various sub-sections (Table 5.4).

Table 5.4 Sections and sub-sections in the HHI questionnaire.

Section	**Sub-section**
Household information	Demographic information on household members; Housing, roofing, fencing; Water sources for domestic water supply.
Vegetation	Reeds, thatch grasses, *Leloli*, wild vegetables, shrubs/debris, medicinal plants, agriculture
Fish	Fish resources
Public health	Domestic water supply, casual drinking; Family health and nutritional information
Sand mining	None
Animal health	Household animals, livestock health, grazing patterns
Religion & leisure	Baptism, swimming, exercising

The aim of the HHI was to quantify the use of all known river resources both within the households and within given periods of time. This information was used to link to the biophysical predictions of change. With every predicted flow-related river change, the social and economic consequences for the PAR could be calculated.

Limitations of the HHIs included:

- lack of baseline data prior to the start of the LHWP;
- gender-specific sections of the questionnaire could not completed if a person of the correct gender was not present when the survey was conducted;
- the complexities of social realities are difficult to capture in a questionnaire.

<u>Interviews with Specific River Users (SRUI)</u> The second method used in the socio-economic survey was to identify community members that used the river for specialised reasons, such as:

- fishers;
- herbalists;
- sand miners/brick makers;
- boat operators;
- forest owners;

- herders;
- vegetable collectors.

A questionnaire was compiled to quantify the economic aspects of this group's interaction with the river. One-on-one interviews were completed with each user group.

Interviews with village chiefs (CI) As is the case in most rural communities, the chiefs are the gatekeepers to communities. The HHI were conducted upon arrangement with the chiefs, who also, along with other community leaders, normally preside over resource use. Interviews with chiefs focused on the following issues:

- demarcation of the primary and secondary corridor of resource use along the rivers and the boundaries between villages;
- information on alternative water sources, such as village water supply systems, springs and river tributaries;
- availability and usage of particular riverine resources.

Outputs

Substantial quantitative data were generated on the use of the study rivers by the PAR. These were used to evaluate the potential social, anthropological, health and economic impacts of river change as a result of altered flow regimes downstream of LHWP dams. In addition to routine demographic data, these included the following.

Resource information

- Identification of the resources used, e.g. water, reeds, grass, sand, wood, fish.
- The species most favoured for use by the PAR.
- The uses made of the resources, e.g. building, handicrafts, food, medicine.
- The importance of each resource to the community relative to other resources (both riverine and other).
- The mean annual amount of each resource harvested.
- The effort required to harvest the resources, e.g. catch per unit effort for fish.
- The number of households that harvested each resources.
- The time of harvest and its relation, if any, to river flow.
- In addition, for plants:
    - the English, Sesotho and scientific name of the plant;
    - the vegetation zone within the riparian zone where the plant was most commonly found.
- In addition, for fish:
    - the English, Sesotho and scientific name of the fish;
    - the relatively sizes of the fish caught and consumed or sold;
    - the condition of the fish.
- Identification of the crops grown in the riparian zone, including:
    - the number of households with fields next to the river;

  - the average size and yield of fields in the riparian zone relative to those outside of the riparian zone.
  - the average proportion of the riparian fields threatened by flooding.

Economic information

- The mean number of units of each resource sold over the preceding year and the preceding five years.
- The mean price per unit of the resource.
- The relative importance of income generated through the sale of riverine resources.

Public health information

The results focussed on household health, the nutritional significance of flow-dependant riverine resources, and the patterns of river water utilisation for domestic purposes and casual drinking. To this end, the study identified:

- the types of disease suffered, and the number of households affected, by age and gender;
- the links between illness and the river;
- the main water supply used for domestic purposes, and how this changed with changes in water availability during climatic cycles;
- the percentage of people who casually drank river water and their frequency of use;
- the percentage of people who had full or partial contact with the river, and the frequency of this contact;
- the consumption of vegetables and fish gathered from the river, by age and gender.

Animal health information

The results focussed on the illnesses associated with the river, and on the amount of contact with the river. To this end, the study identified:

- the number of animals in the study area;
- the patterns of ownership and watering of animals, and the dependence on the rivers during different times of the year;
- the diseases and illness suffered, and their prevalence, by species;
- the links between diseases and illness and the river;
- physical dangers associated with the river, such as becoming bogged down in mud;
- the number of animals that had suffered (or died) in any way related to the river within the previous 12 months.

Cultural information

The rivers in Lesotho are used for various cultural and religious ceremonies and leisure activities. Thus, information was gathered on:

- use of the river for baptism, or other ceremonies, and which parts of the river were most important, e.g. pools;
- conditions required for baptism or other ceremonies to be possible, e.g. water quality, depth;
- use of the riverine area during initiation and other rituals;

- use of the river for various sports, e.g. swimming, running, stick fighting and horse riding and the conditions required;
- use of the river for personal hygiene and clothes washing and the conditions required;
- the availability of, and willingness to use, alternative sites.

Other information

- perceived changes in flows in the river over time;
- positive and negative views of floods and lowflows;
- legends and myths surrounding the river, e.g. the river snake;
- the relationship between songomas, ancestors and the river snake;
- the availability of, and willingness to use, alternative sites;
- potential for ecotourism associated with the river;
- hunting of animals such as birds and mammals in the riparian zone.

Results/Findings

A summary of the predictions made by Metsi Consultants (2002b) in the Lesotho was that under the different scenarios the downstream impacts would differ in the following ways.

- Under the Treaty Scenario it was predicted that there would be a considerable loss of wild vegetables, medicinal herbs and fish. This would lead to a reduction in the availability of these resources impacting on nutritional levels for communities dependent on them. It was predicted that as a result of changes in flow there would be a deterioration of downstream water quality impacting on the health of downstream users. The study found that the most important impact along the river under this scenario would be the loss of fuelwood as trees and shrubs were lost from riverine vegetation.
- Under the Design Limitations Scenario impacts would be severe in communities along the Malibamat'so River downstream of Katse Dam, moderate downstream of Mohale Dam and Matsoku Weir, and low further down the system. Under this scenario it was found that the important resources, such as fuelwood, and nutritional resources such as fish and wild vegetables, would suffer the same decline as in the Treaty scenario.
- The Fourth Scenario was designed as a midpoint between the Design Limitation and Treaty scenarios. The study findings were that under this scenario the general impacts on resources and therefore communities would be less severe than for the Treaty scenario.

5.4.7 South Africa – The Sabie River Environmental Flow Assessment

Objectives

As part of the work done to assess the Ecological Reserve for the Sabie River, Mpumalanga, a study was undertaken of the river resources used by people living alongside the river. This provided a qualitative assessment of their dependence, if any, on a healthy riverine ecosystem (Pollard & Simanowitz 1997). The study focused on two villages; Madras and Belfast, alongside the Sabie River using the approach.

Process

PRA methodology and individual interviews were used to obtain information from the villagers. As data were gathered, a progressive understanding of, and support for, the use of environmental flows to maintain river health developed in the villagers. Key focus groups interviewed included general community members, women's groups, church members, farmers, *t'inangas (healers)* and fishermen.

Information was gathered to establish the following:

- the river resources that are used;
- the location of the resources used;
- the extent of the resource;
- who makes use of the resources (individuals or groups);
- the importance of the resource as a livelihood source;
- whether there are any areas of conflict around resource use;
- timing of resource use.

The seasonality-of-use or *when* the resource was used, illustrated the initial link with flow. Subsequent discussion on changes in resource availability with variations in water levels provided the opportunity to evaluate the quantity and seasonality of flow needed to maintain a particular resource. This could then be further evaluated in terms of the expected impacts if the resource was to be reduced or disappear.

Outputs

The study provided an assessment of the use of freshwater fish as a resource for riparian communities and a qualitative assessment of their dependency on fish as a protein source. The importance, seasonal availability and preference for the different species of fish were ranked. Species were also ranked on seasonal availability.

5.5 Lessons learnt: guidelines for the social component of environmental flow assessments

5.5.1 Introduction

The consequences for a downstream riparian community of flow-related changes in river resources are dependent on four main factors:

- the extent of flow modification;
- the extent to which used river resources are linked to flow;
- the extent of use of the resources by the communities;
- the degree of dependence of the communities on the resources.

Additionally, the consequences for the health of the people and their livestock will depend on:

- the extent of river use by communities or their livestock;
- the extent to which river-related health issues are linked to flow.

The effects of changing resources or health profiles are often unclear because they may lead to changes in behaviour patterns. For example, a reduction in one fish species may simply result in a different species being fished using a different method, with little on no impact on the nutritional status or traditions of a community. Health impacts are especially challenging to understand because of the wide range of other (non-flow related) factors influencing community and livestock health. Also, change in the livelihood circumstances of one household may have a knock-on effect on other households (Turton 2002), making flow-related impacts difficult to understand and predict. Yet it is this process - to understand the links between rivers and subsistence users and use this to predict how they might be affected by flow changes – that is the essence of the social component of an EFA.

5.5.2 Disciplines required for an EFA-linked sociological study

Local circumstances and requirements will affect almost every aspect of an EFA, including the disciplines required for the social and biophysical components of the study. Typically, the sociological components could require input from specialists in the following disciplines:

- anthropology;
- sociology;
- public-health medicine;
- veterinary science;
- water supply;
- resource economics.

They will have to interact with a biophysical team that is developing an understanding of the functioning of the river as an ecosystem in order to predict how it could respond to flow changes. The biophysical expertise will probably be in the fields of:

- hydrology;
- hydraulics;
- geomorphology;
- sedimentology;
- water quality;
- riparian and aquatic botany;
- aquatic invertebrates;
- fish;
- others.

The other fields involved could be microbiology, if disease organisms and parasites are of importance, or biologists knowledgeable in water birds, semi-aquatic mammals, frogs and reptiles.

Initially, the social team needs to be able to inform the biophysical team of river species or features of importance to the riparian communities so these can be included in their studies. Later, when their studies are complete and scenarios of flow change-river change have been created, the social team should be able to evaluate each scenario in terms of its impact on the communities. One of the scenarios should always be 'no change'.

5.5.3 Scheduling the EFA-linked sociological studies

The methods used to assess the impacts of flow changes on riparian communities are similar regardless of whether the impacts have occurred or are predictions. However, the order in which various activities are undertaken can be expected to differ (Figure 5.1).

If, for instance, the impacts have not yet occurred, the following sequence of activities could be followed:

1 Identify and quantify the Population at Risk (PAR)
- the number and distribution of people using the aquatic ecosystem resources;
- the health status of the PAR;
- the health status of the PAR's livestock.

2 Identify the PAR's use of river resources
- the aquatic ecosystem resources being used by villagers

3 Identify and quantify the PAR's interactions with the aquatic ecosystem
- the extent of use of aquatic resources;
- the extent of dependence on the aquatic resources;
- the extent of contact with the aquatic ecosystems, and the possible implications for the health of villagers or their livestock should the condition of the system change;
- possible alternative sources of aquatic ecosystem resources;

4 Ascertain the links to flow
- the links between the resources being utilised and flow from upstream;
- the links between factors that could influence community health (such as disease vectors, nutrition, water quality) and flow;

5 Develop scenarios
- the manner in which the flow-linked resources and health factors were expected to change with changes in flow;
- the resultant impact on resource availability, and the risk of health problems;
- consequences for the PAR of the scenarios described by the biophysical team.

The scenarios provide the basis for the decision-making process. One scenario is usually ultimately chosen and implemented. Thereafter, the following post-project activity should ensue:

6 Monitor post-development affects on the PAR:
- changes in resource availability;
- changes in health profiles;
- changes in village life-styles and traditions;

- use of alternative sources of aquatic ecosystem resources.

Where the impacts have already occurred, some attempt at post-development assessments of change (step 6) may well have been done in the absence of an EFA. If an EFA is initiated, however, the above sequence could still then apply.

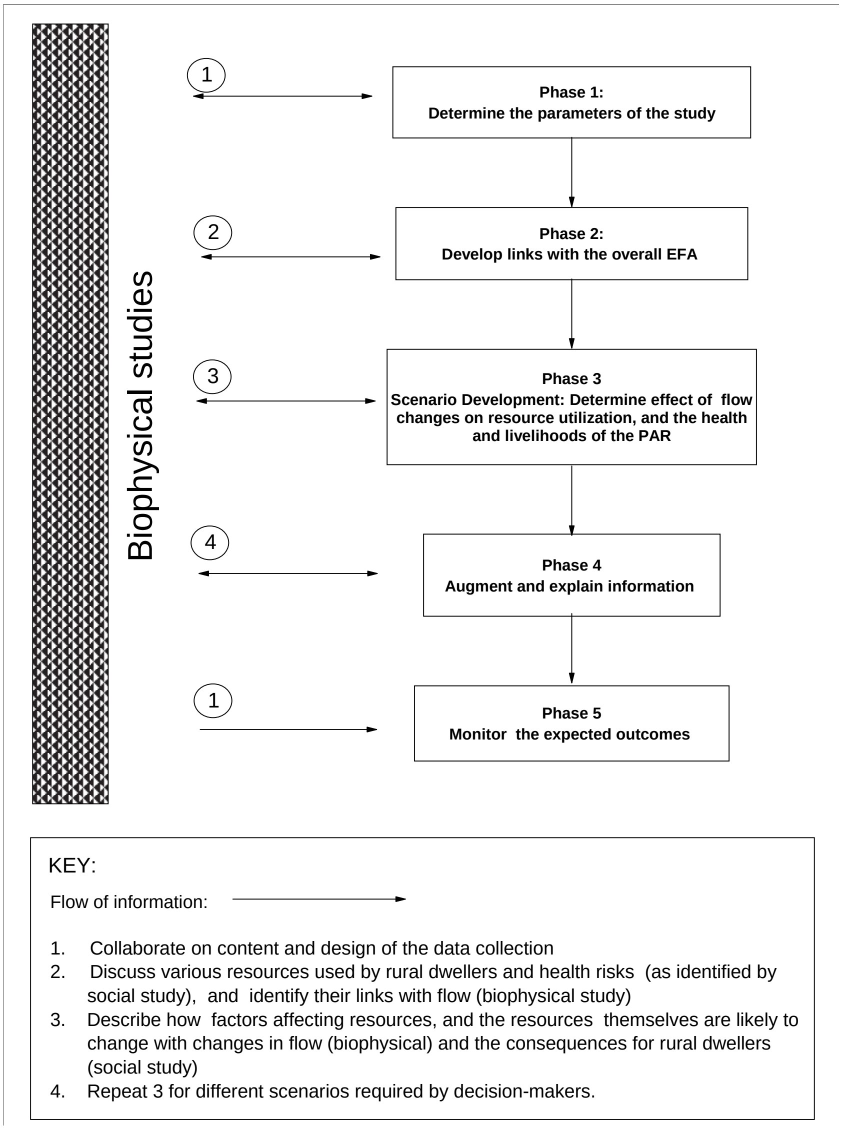

Figure 5.1 Schematic diagram illustrating the multi-phased approach suggested for EFA-linked sociological studies.

5.5.4 A multi-phased approach to the social studies

The inherent complexity of interactions between humans and aquatic ecosystems usually necessitates a multi-phased approach to an EFA sociological study (e.g. Horowitz *et al.* 1991, Metsi Consultants 2002a) similar to that described below:

1. Phase 1, or pilot, study: undertaken to determine the parameters of the study (Steps 1 and 2 in Section 5.5.3);
2. Phase 2, a detailed, quantified socio-economic study aimed at developing the links with the overall EFA, and confirming or refuting information gathered in the pilot study (Steps 3 – 4);
3. Phase 3, scenario development, a multi-disciplinary phase aimed at determining how river changes described by the biophysical team are likely to affect resource utilisation and the health and livelihoods of the PAR (Step 5);
4. Phase 4, an optional final phase in which the social team respond to additional scenarios requested by the decision-makers.

Once the decision-makers have selected a scenario, the EFA is complete. Thereafter, EF-related activities of the social team should be aimed at two main activities:

- design and implementation of a programme to monitor the expected outcomes to the PAR of releasing the chosen EF;
- further quantification of the likely impact of predicted resource losses on the PAR, in order to calculate compensation costs of, for instance:
  - replacement wood lots;
  - replacing fuel-wood with fossil fuel;
  - village horticultural programmes to replace wild vegetables;
  - hatcheries for stocking the river with fish;
- design and implementation of public-health and animal-health programmes aimed at reducing or preventing predicted health impacts.

The four phases are detailed below, but the post-EFA activities are not covered in this report.

5.5.5 Phase 1: Defining the parameters of the study

Data collected during the social assessment must be relevant to the overall objectives of the EFA, and should be able to be interpreted by the biophysical specialists. Thus, the social and biophysical specialists should collaborate on the design for data collection (Pollard 2000). Indeed, liaison between the biophysical and social specialists should be a central and ongoing part of any EFA.

Phase 1 has important implications for the biophysical components of the EFA, as the biophysical specialists must be able to include any resources being used by the PAR in their studies. It is also during this phase that the extent and usefulness of local indigenous knowledge become apparent. This knowledge needs to be documented and understood by all participants, and community knowledge accorded its proper place in the mix of required expertise (Mubvami pers. comm., in Brown & King 2002a), particularly in developing countries where published data are often scarce. For example, local herbalists are often able to assist the botanical specialists with identifications and life histories of commonly-used plants (Metsi 2000g).

Phase 1 is for the most part an open-ended, anthropological and participatory exercise aimed at developing a conceptual understanding of the PAR, their interactions with the aquatic ecosystem and the resources that they are using. This will assist in the development of questionnaires, the identification of key interest groups and the selection of study villages for Phase 2. Included in Phase 1 should be an assessment of the baseline heath status of the PAR and their livestock.

Identification and quantification of the Population at Risk (PAR)

Definition of the PAR usually forms part of the initial social assessment, and should coincide with the study area defined by the biophysical team. Resource use within this study area is likely to be determined by factors such as (e.g. Metsi 2000g):

- ownership;
- traditions, customs and tribal laws;
- poverty levels;
- topography;
- infrastructure, e.g. road and bridges;
- access to alternative resources.

The influence of these, and possibly other, factors on resource use will need to be determined before the PAR can properly be identified and delineated. Thereafter, population census data can be used to determine the demography of the PAR.

Identification of flow-linked resources used by the PAR

Key questions used by Taylor *et al*. (1995); Metsi Consultants (2000g); and Brown & King (2002b) included:

- what animal and plant species does the PAR use;
- which of these are associated with the study river/ wetland/estuary/floodplain;
- does the PAR use other resources from the river/wetland/estuary/floodplain, such as sand or mud for building or water from drinking;
- is floodplain or flood-recession agriculture practiced, and if so, when and where?

Other questions related to leisure-and cultural-use of the systems are also important. For instance:

- is the river/wetland/estuary/floodplain used for cultural events;
- if so, which features such as waterfalls and pools are used;
- what time of the year are they used;
- is the river used for recreational activities and, if so, when;

- what is the general feeling about the river/wetland/estuary/floodplain - is it liked, feared or hated?

It is vitally important at this stage that the PAR is drawn into the study via people who can communicate effectively with the people. Most researchers (Fisheries Office 2000, CRES 2001) advocate a participatory approach for data collection, arguing that strict adherence to a questionnaire does not allow for explanation or exploration of new issues raises by the community.

Ascertaining the baseline health status of the PAR

The investigation of health issues affecting the PAR should begin with a review of available documentation, such as results of previous studies and relevant international literature.

Key questions by Phillips (1999) included:

- what are the main health concerns in the area;
- what is the age-specific nutritional status of the community;
- which, if any, health concerns are linked to the river/wetland/ estuary/floodplain, either directly (e.g. bilharzias), or indirectly (e.g. nutrition obtained from river/wetland/estuary/floodplain resources)?

Additional data to assess predicted flow-related changes of the river will probably be required in Phase 2.

Ascertaining the baseline health status of the PAR's livestock

As with the public health component, the investigation of health issues affecting livestock in the study area should begin with a review of available documentation such as local and regional veterinary records, results of previous studies and relevant international literature.

Key questions by Phororo (1999) included:

- what are the main livestock health concerns in the area;
- to what extent is the river/wetland/estuary/floodplain used for grazing or watering of cattle?

5.5.6 Phase 2: Quantifying interactions with the aquatic ecosystems

Phase 2 is a data collection phase. It could have two main parts.

1. Research
    a. confirm or refute information gathered in the pilot study and, where possible, quantify resource use
    b. collect health-related primary data and possibly microbiological and parasitological studies.

2. Intensive liaison between the biophysical and sociological teams
   a. inform the biophysical team of **all** flow-linked issues raised in the sociological studies;
   b. ensure biophysical and social data sets are linked e.g. plant resources used are known by species name;
   c. ensure the social team understands and can work with the information on river change emanating from the biophysical team.

Quantification of the PAR's interactions with the aquatic ecosystem usually necessitates field surveys. Numerous appraisal methods exist or have been/can be adapted for use in this phase of an EFA. Some are outlined in Section 5.4 (Fisheries Office 2000; CRES 2001; Bielfuss *et al.* 2002; Metsi Consultants 2002a). The specific questions and interest groups comprising these appraisals will differ considerably from area to area, but the principles remain similar throughout. The kinds of information required for the EFA will probably also remain fairly similar, with examples below.

General resource utilization

For each resource that was identified in Phase 1, the following questions should be answered.

- What purpose is it used for?
- When is it collected and from where?
- How much is collected and when?
- Who collects it?
- Are there alternative resources available? Would it be possible to provide alternative resources?
- Are there critical water levels associated with each resource? Which seasons (and hence discharges) are important in terms of use or maintenance of the resource?
- Has the resource changed with time and perceptions on why?
- What is the level of dependence of the PAR on the resource?
- Is the PAR's need for the resource being met? If not why?
- What laws/customs, if any, govern use of the resource?

Water use

- Is drinking water collected from the river/wetland/estuary/floodplain? If so, where is water collected and at what time of the year?
- Are animals watered at the river/wetland/estuary/floodplain? If so, at what time of the year?
- Is the river/wetland/estuary/floodplain used for washing? If so, in which area?
- Is the river used for irrigation of crops?

Agriculture

- Are any of the fields/crops dependent on flooding? If so, which crops and how often are the fields flooded?
- Where are the fields?
- When are they planted and harvested?

Cultural use and perceptions

- Is the river used for cultural events? If so, what are these events and which features of the river are used? What time of the year are they used?
- Is the river used for recreational activities and, if so, when?
- Does the river/wetland/estuary/floodplain present any problems or dangers to the local people, such as flooding, difficulty crossing, or danger from wild animals such as crocodiles and hippos?
- What is the general feeling about the river? Is it liked, feared, hated?

Income generation

- Does the river provide a source of income at a local, regional or national level? This could be through the sale of “unimproved” riverine resources, such as cobbles, fish, wood or herbs, or “improved” resources, such as bricks made from riverine sand or baskets from river reeds.
- What is the value, in monetary terms, of the river/wetland/estuary/floodplain resources used by the PAR?
- Does the river provide income generated through other activities, such as tourism (e.g. weekend cottages, rafting trips, hiking) or transportation (e.g. boats, ferries).
- What is the value of the river as a realised or potential tourist attraction?

Public health issues

- What is the level of nutrition derived from each river/wetland/ estuary/floodplain resource used?
- What is the frequency with which the river/wetland/estuary/floodplain water is used for drinking or cooking purposes?
- What is the frequency of different types of river use, e.g. direct or indirect use?
- What diseases, accidents or disabilities have household members suffered within the last two months?

Phase 2 should also comprise some health-related primary data collection on the incidence and temporal nature of diseases and illnesses suffered by the PAR. The main outcome of these surveys should be identification of possible new health threats that could arise as a result of changes in flow.

Animal (livestock) health issues

- What is the level of nutrition derived from riparian grazing?
- What are the main livestock diseases in the area, and are they linked to the river?
- If flows were to change, would this health profile change?
- What is the frequency of different types of river use, e.g. stock drinking, river crossing?
- Does the river play a role in animal control (for instance by preventing animal crossing to another village's fields), and if so, what is its role?

Knock-on effects

The sociological team needs to be alert to possible knock-on effects of flow changes. Examples include:

- reductions in low flows → facilitate animals crossing river to adjacent villages → more herdboys required to control cattle → fewer herdboys attending school;
- changes in river flow → reductions in fish → fishermen leave village in search of work → change in social structure of the village;
- reduction in lateral flooding → reductions in wild vegetables growing alongside the river → fewer vegetables eaten by community → trace element deficiencies → increased incidence of disease and malnutrition.

5.5.7 Phase 3: Assessing how flow changes could affect the PAR

Determining the links between flow and the PAR, in order to predict how flow changes will affect them, is a multi-disciplinary exercise. The first part of the link, of how the river could change, should be provided by the biophysical specialists. This can be done by describing in a series of scenarios with different flow patterns how each resource could change from present (see King *et al.* 2003), in terms of:

- the direction of change (increase or decrease in abundance);
- the extent of change;
- the expected impact on river condition, relative to natural.

The biophysical scenarios are the template for development of social scenarios and their economic implications. For each scenario, site and resource, impacts can be ranked as none, low, moderate and severe, using expert opinion and the data collected during Phases 1 and 2, considering the following issues (Metsi Consultants 2000e):

- the level of predicted change of a resource;
- importance of the resource for the livelihoods of the affected populations;
- number of households harvesting the resource;
- frequency of usage of the resource;
- availability of alternative resources.

Social impact is probably best defined in a series of broad categories, e.g.:

No impact: No appreciable change in the resource is expected.

Low impact: The resource is not important or, if important, its quantity is predicted to change less than 20%.

Moderate impact: The resource is important, and its quantity is predicted to change by 20-50%.

Severe impact: The resource is considered essential for the livelihoods of the PAR; **and** it is used by >20% of the PAR households; **and** the predicted biophysical change is > 50%.

In addition, the public and animal health specialists should assess for each scenario the impacts on health profiles, in terms of: new diseases or illnesses; an increase in present ones; or a change in nutritional status due to the loss of river plants or animals. Impact assessment could be based on

- the fact that a wide range of factors influence health in the PAR, some of which will have no links to the river;
- the pre-impact health status of the community;
- the extent of river use by members of the PAR;
- the predicted biophysical changes that could influence peoples' health.

Table 5.5 provides an example of the considerations that were used to create the links between biophysical changes in the river and listed PAR health concerns in the Lesotho Highlands EF assessment (Metsi 2000g). The column 'Ecological link' lists some parts of the ecosystem that could change with a flow change, and an explanation of how this could affect people and their livestock. The weighting indicates the importance of this to the health issue under discussion. The 'Onset' entry indicates the time span over which the impacts described in column 1 may become apparent.

5.5.8 Phase 4: Augment and explain the information

Augmentation and explanation of the information is suggested as a separate phase because the time and effort required to ensure that the information is delivered properly and understood correctly by decision-makers, engineering and other professionals and stakeholders is often underestimated. Effective communication of the results of an EF assessment requires that considerable attention be paid to summary presentations in clear, non-jargon language that can be used in management decisions.

Table 5.5 Examples of health-related ways a river ecosystem could change, and the relevance of this for diarrhoeal and eye and skin diseases among the PAR (Metsi Consultants 2000e). Columns 1 and 2 should be considered together. Explanation in text.

Ecological link	**Weighting**	**Onset (years)**
Colloids With an increase in colloidal material diarrhoeal, disease-causing organisms such as *Giardia* remain in the river for longer, thus increasing the chances of people becoming infected either through contact (skin and eye infections) or consumption (diarrhoeal disease).	High	2-10
Total Dissolved Solids Drinking turbid water with high TSS levels does not necessarily have direct health effects, but such effects can occur when infectious disease agents adsorb onto the particulate matter.	High	2-10
Algal blooms High summer flows flush algae from the river, but low winter flows allow the plants to accumulate in quiet areas. Loss of flushing flows will increase the risk of algal blooms, with resulting adverse health effects through swallowing algae-contaminated water	High	1-2
Black flies Increases in the numbers of blackflies can result in an increase in the level of irritation caused by their bites. Blackflies can also carry disease from faeces to food or utensils used by humans (faecal – oral route).	Low	1-2

5.6 Conclusion

This review has illustrated that the impact of loss of river resources to riparian communities downstream of water developments is little understood. Emerging evidence suggests that the existing and potential impacts of these losses are high (e.g. McCully 1996; Beilfuss *et al.* 2002). It is crucial that these downstream impacts be clearly documented or, in the case of a proposed development, predicted. Without an understanding of the actual or potential impacts and their long-term economic implications, the information supporting and rationale behind decisions relating to such developments are essentially flawed.

Undertaking an EFA does not guarantee that the impacts of a water-resource development will be eliminated. Even if implemented, an EF can only partially mitigate against the effects of the development. For instance, the physical presence of a dam will, in itself, impact the downstream river through, *inter alia*, trapping sediment, reducing flow variability and changing temperature and chemical profiles of the downstream system. Nothing is gained at no cost – if flow regimes are manipulated, the targeted rivers will change (Brown & King 2002a). The EF methods now under development in South Africa, however, do allow prediction of both the biophysical and socio-economic impacts of such projects, which is a first step in a more holistic approach to decision making. As yet, there are relatively few examples of sociological studies contributing to EFAs in this manner. There are even fewer where the decision-making process is transparent enough to enable an assessment of the extent to which the results of the EFA assisted in, or influenced, the final decision on the operation or construction of a water-resource development. The ones that have been completed have nevertheless attracted a disproportionate amount of attention and the trend is probably toward their more extensive application.

A relatively standard set of procedures and protocols would facilitate incorporation of sociological data into EFAs, and a first attempt at compiling such is provided in Section 5.5. This is intended to stimulate discussion on the possibilities for and approach to the development of a set of procedural guidelines for the sociological module of an EFA.

6. PARALLEL APPLICATION OF THREE ENVIRONMENTAL-FLOW ASSESSMENT METHODS IN THE BREEDE RIVER BASIN STUDY

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6.1 Introduction

6.1.1 Background to the study

In October 1999, Southern Waters Ecological Research and Consulting cc ("Southern Waters") was appointed by a joint-venture comprising MBB, Ninham Shand, and Jakoet and Associates to determine the water-quantity component of the Ecological Reserve for the main rivers within the Breede River Basin.

The study was conducted as part of the wider Breede River Basin Study (BRBS), which was commissioned by the Department of Water Affairs and Forestry (DWAF) in August 1999. The MBB-Shand-Jakoet joint-venture was the lead consultant for the Basin Study.

As a separate, but related exercise, the Water Research Commission (WRC) and DWAF agreed to fund a parallel application of three flow-assessment approaches to some of the Breede River study sites. The approaches are the Building Block Methodology (BBM) (King & Louw 1998); the Flow-Stressor-Response Approach (FSR) (O'Keeffe *et al*. 2002); and Downstream Response to Imposed Flow Transformations (DRIFT) (King *et al*. 2003, Brown & Joubert 2003). All three approaches were to be applied to the same set of sites on the Breede system, using the same river scientists and the same sets of data. The lead-up to this exercise is recorded in Report 2 of the BRBS series (Section 1.3).

6.1.2 Objectives of the parallel applications

- Apply three flow methods, the BBM, FSR, and DRIFT, to the same river system, using the same specialists and data.
- Update all involved in the exercise as to the nature and latest developments of the three methods.
- Assess the advantages and disadvantages of each method and compare their outputs.
- Implement, and contribute towards the development of, the FSR method.
- Assess how the methods could be amalgamated into one or, alternatively, describe the circumstances in which each could be used.

6.1.3 This report

The parallel application yielded a series of reports.

REPORT 1: The BBM application, as per the original contract, containing recommended flow regimes for each of six representative sites in the Breede River Basin (DWAF 2003).

REPORT 2: The DRIFT application, providing three flow scenarios for each of three of the sites used for the BBM application. For each scenario at each site, the potential future flow regime is described, together with the biophysical consequences for the river (Brown and King 2002c).

REPORT 3: An assessment of the overall nature, similarities, differences, strengths, weaknesses and outputs of each of the three approaches, using two sites to which all three were applied.

This chapter is REPORT 3 in the series.

The theory behind and the application of the FSR method is provided in O'Keeffe *et al*. 2002, and the application in the Breede River Basin Study was not written up as a formal report. However, an outline of the method and the explanation required for comparison of the three methods are reported here.

> Note: The process for quantifying the Reserve is itself evolving, but it seems likely that the various major steps will not fundamentally change. Much of the terminology is still changing, and we have tried to use the most up-to-date terms in this report.

6.2. The three approaches in the context of flow assessments and the Reserve

Assessments of the Reserve within any one catchment, as required by the South African Water Act of 1998, include setting water quality and quantity requirements for basic human needs, and for the protection of all relevant water bodies. The water bodies for which Ecological Reserve assessments should be made include rivers, wetlands, lakes, estuaries and groundwater, and eventually will include impoundments also.

The three approaches dealt with in this Report are all designed for use in the quantity aspect of the Ecological Reserve for rivers. They all address environmental flow requirements for rivers.

An assessment of this flow requirement can be made wherever there is a need to manage the condition of the river ecosystem. Such a requirement might arise when a new water-resource development, such as a dam, is being contemplated, when there is a wish to rehabilitate a degraded river, or in regional planning where no specific development is anticipated or present. Whatever the purpose, the flow assessment should provide a number of scenarios for consideration by the water manager. Each scenario should consist of, as a minimum, a potential flow regime for the river together with its consequences in terms of river condition and yield of water from the river.

Two main flow-assessment methodologies (groups of inter-linked methods) have been developed and applied in southern Africa for comprehensive environmental flow assessments: the BBM and DRIFT. The FSR is a semi-holistic approach in development. All are designed to predict changes that will occur in a river ecosystem when its flow regime is manipulated. To varying extents, the approaches can also be used to inform on the implications of these river changes for subsistence users of the river's resources.

The BBM and DRIFT are *holistic methodologies*, that is, they:

- address both the living and non-living features of the river;
- address any relevant part of the river ecosystem: the channel, banks, floodplains, estuary, and associated wetlands and groundwater;
- address all parts of the flow regime, distinguishing high and low flows, and wet and dry seasons;
- employ a range of specialists from the following disciplines:
    - hydrology;
    - hydraulics;
    - fluvial geomorphology;
    - sedimentology;
    - aquatic chemistry;
    - botany (riparian, marginal and aquatic vegetation);
    - zoology (fish, aquatic invertebrates, (and sometimes water birds, aquatic mammals, micro-organisms));
    - sociology (in DRIFT, there may be a full team consisting of sociologist, anthropologist, water-supply specialist, human-health medical doctor, livestock veterinarian, resource economist).

The FSR has some of the same attributes.

In all three approaches, the specialists gather data on the river, in a preparatory set of activities. All three methods can comply with the five-step RDM process. These steps are designed to develop understanding of the undisturbed and present nature of the river, and to develop predictive capacity of how it would change with flow changes. This predictive capacity is then accessed in flow-assessment workshops or similar activities, where the full team describes, in the way the different approaches require, the links between flow and ecosystem response. These links are ultimately used in the development of scenarios.

The five-step RDM process that each follows can be summarised as follows (latest version provided by email by Harrison Pienaar of the RDM Directorate on 13 October 2003):

Step 1: Initiate RDM Study. This entails management decisions about the scope of the study. It involves delineation of the study area; definition of the appropriate level of Reserve Determination and the aquatic ecosystems for which Reserves shall be determined (e.g. rivers, groundwater, estuaries, wetlands); and definition of the composition of the study team.

Step 2: Define the Resource Units and select a site. The step involves ecotyping and zonation assessments, which help inform on the nature of the catchment and river, and guide site selection. A habitat-integrity assessment is also often done, to further aid site selection and understanding of the nature of the river. All three approaches are site based, using representative or critical sites along the river to represent conditions in the river as a whole. The sites act as foci for data collection and analysis, allowing specialists to build up an understanding of the river. Ultimately, a flow assessment is done for each site.

Step 3: Define Ecological Categories and recommend an Ecological Category: The definition of Reference Condition (RC), Present Ecological State (PES), trajectories of change in PES and determination of Ecological Importance and Sensitivity (EIS) are done in this step. The PES and EIS together inform the recommendation of a future Ecological Category. Flow scenarios for the recommended Ecological Category and various other categories are then generated. This is where the different methodologies for the quantification of environmental flows are applied (i.e. BBM, DRIFT or FSR). DRIFT and the FSR provide increased consistency and more detailed assessments of alternative scenarios than does the BBM, and as such the ecological consequences of different scenarios can be generated without reconvening the specialist teams (although it is recommended that the outputs be checked by key specialists). The BBM requires that the ecological consequences of each new scenario be deliberated individually at additional specialist workshops.

Step 4: Reserve specifications: This is an internal DWAF process.

Step 5: Implementation Design: This is an internal DWAF process.

6.3 Comparison of the overall approach of the three methods

In Step 3 of the RDM Process, the methods diverge in terms of the process used to produce the flow assessment.

6.3.1 The BBM

The BBM was designed between 1990 and 1994 following DWAF requests that environmental flows be defined in terms of magnitudes, frequencies, timing and duration of different kinds of flows. It was also required that all recommended flows be justified. At that stage there was no process in place for deciding on the desired future condition of a river and, indeed, little understanding either that rivers could be maintained at different conditions or what the links between flow and condition were. In reality, the river scientists were being asked to define flow regimes to maintain rivers in unidentified conditions. To resolves this, it was agreed that the scientists would recommend a best feasible condition for the target river, and define a flow regime to facilitate achieving and maintaining this. This recommended ecological condition has become known as the Ecological Category (EC). Because of the way it was structured to meet

DWAF needs, including the need for a pre-defined EC, the BBM emerged as a prescriptive method that identifies an objective (the EC) and prescribes the flows to achieve it. This EC may be modified later through the consideration of several Operational Scenarios, with the final product being a Management Class that will be society's agreed target condition for the river.

Essentially, the BBM uses the natural (RC) and present (PES) condition of the river, and the natural and present flow regimes, as its starting points. Knowing these and with strong reference to the reference condition, the EC is identified, and the flow regime to achieve this described. The flow regime is compiled from scratch, by adding, one at a time, flow components such as specific sized floods, freshes or low flows at specific times of the year. All added flows are motivated for, in terms of the ecological attributes they would sustain. Because flow components cannot be added without motivation, there is a possibility that the final flow regime will be too low in total volume. This reflects our present understanding of rivers – different sized flows may maintain rivers in many ways that we do not yet understand and so they are not motivated for.

With time, it became apparent that the outputs of the BBM were poorly suited for use in negotiations. If the one prescribed flow regime could not be met because of other water demands, the whole process had to be repeated with another EC and flow regime. Thus, new tools evolved to allow development of several additional scenarios (e.g. the Desktop Model, Hughes & Münster 2000; Box 1). The Desktop Model produces outputs that also meet the needs of the new Reserve legislation. The flow regime for the recommended EC is used to calibrate the Desktop Model, which can then be used to derive alternative flow regimes for other adjacent categories of river condition (i.e. alternative ECs). Finally, the specialists assess if these alternative flow regimes would indeed achieve the river states indicated by the Desktop Model.

The main strengths of the BBM approach are that:

- it meets DWAF requirements in terms of outputs and the Ecological Reserve:
    - environmental flows are defined in terms of magnitude, duration, frequency and timing;
    - all recommended flows are motivated for;
- it can be used to define a flow regime for a specific river state or objective;
- the specialist group reach consensus on the recommended flow regime;
- it can produce scenarios through the Desktop Model link;
- it can be used for regional planning of water resources where general agreement exists about the future condition of a river;
- it can incorporate any relevant knowledge on the river;
- there is a comprehensive manual for its application (King *et al.* 2000a).

Box 6.1 The Desktop Model (Hughes & Münster 2000)

The Desktop model provides a low-confidence estimate of the quantity component of the Ecological Reserve for rivers. It was developed in response to the need for a number of very quick estimates where the application of the more detailed Intermediate or Comprehensive Reserve determinations was not considered appropriate. Such situations could arise when the degree of water-resource development in a catchment is relatively small and no serious conflict between the requirements for the Reserve and water users are expected, or when a rapid method is required for pinpointing likely problem areas in a catchment in advance of selecting sites to carry out more intensive, higher confidence estimates. The method is based on a generic regionalisation of past environmental water requirements (EWR) that were assessed using the BBM. As such, it is recognised that there may be site-specific ecological or geomorphological considerations for which the Desktop method will generate under- or over-estimates of the Reserve.

The method consists of four main steps:

- The use of a relationship between a hydrological index of flow variability and the annual EWR for maintenance low flows, maintenance high flows and drought low flows for different Ecological Categories (EC).
- The use of regionalised seasonal distributions of baseflow contribution to divide the annual totals into seasonal distributions of EWRs for the three components (maintenance high and low flows and drought low flows).
- The use of regionalised % assurance curves to specify the frequency of occurrence relationships of the defined maintenance and drought requirements for each month.
- The generation of a representative time series of monthly flow volumes using the time series of reference flows (WR90 by default) to provide the climatic cues to determine when to select required flows within the range between drought and the maximum.

Its weaknesses are as follows.

- Once the recommended EWR has been determined, alternative EC scenarios are generated using the Desktop Model and as such have no ecological detail linked to them. They are assessed for ecological relevance by the specialists.
- It is more subjective than the other methods and thus susceptible to the mindset of individual specialists.
- Because of the direct link between a particular flow and its justification, the specialists are open to pressure during the workshop to reduce their recommended flows.
- The alternative flow regimes produced by the Desktop Model cannot be used to further calibrate the Desktop Model (the Model should not use its own outputs to re-calibrate itself).
- Its outputs are prescriptive – all scenarios are accompanied by a motivation for the flows that are required. The consequences of not meeting flows are described at a lower level of

detail than in other methods.. This makes it difficult if not impossible to determine the ecological consequences of not releasing a particular flow.

- The ecological consequences of alternative flow scenarios need to be evaluated individually at additional specialist workshops.

6.3.2 DRIFT

DRIFT began development in 1996 in response to two recognised needs that the BBM did not meet: to be able to produce comprehensive scenarios, and to include in them structured and quantitative information on subsistence use of river resources.

DRIFT also uses the natural and present condition of the river, and the natural and present flow regimes, as its starting points, but the emphasis is on describing how the river will change from its ***present condition*** as that is the condition that the specialists can study and understand. The present and reference condition assessments are done through literature searches and on-site data collection, and the flow assessments through analyses of ten flow categories (dry-season low flows; wet-season low flows; four size classes of intra-annual floods; four size classes of inter-annual floods). Statistics derived for the flow categories include the range of low flows in each season, and the average number, duration and magnitude of each kind of flood. These statistics help the specialists to understand the nature of the flows that have contributed to the present condition of each study site. Each of the flow categories is then taken through a series of theoretical reductions, or additions, in their number (floods) or magnitude (low flows), and the specialists predict how the river will change from its present condition with each of these flow changes. All of the changes are entered into a custom-built database, which can then be queried to describe how any possible future mix of high and low flows is likely to change the river. In this way, any number of scenarios can be produced very quickly once the database is populated. The predicted changes are given in detail, and quantified (e.g. with reduction of the Class IV floods from six per annum to three per annum, a specific community of riparian plants will be reduced by 20-40% of its present extent, whilst if the Class IV floods are reduced to none per annum, the same plant community will be reduced by 70-90%). Uncertainty is expressed through increasing the range of predicted change (e.g. a 20-40% change implies higher confidence in the prediction than a 20-80% change). DRIFT is not prescriptive, and does not pre-identify one desired river condition (i.e. one EC). Rather, each of the scenarios it produces describes one possible future flow regime linked to one category of river condition. This provides many detailed options for consideration by stakeholder groups, for macro-economic analysis and, ultimately, for a political decision. From these other activities, the scenario chosen in Step 6 of the RDM process becomes the desired condition for the river (i.e. the Management Class), and its flow regime becomes the environmental flow to be managed. When applied as part of the RDM process, the specialist team recommends one of the scenarios as the EC.

Although DRIFT has mostly been used to guide decisions on potential water-resource projects that would abstract water from a river system, it can equally be used in river rehabilitation projects, where it would produce scenarios of river changes linked with the introduction of more beneficial flows; or for defining flows to meet a particular ecosystem objective; or in regional planning (as was the case at Site 1 in the Breede River Basin Study).

In total, DRIFT consists of four modules. The data-collection and analysis activities of the biophysical team, mentioned above, comprise the first module. Module 2 addresses the relationship between subsistence users of the river and flow, in terms of resources used and health levels. Module 3 uses the outputs of Modules 1 and 2, to generate both a range of biophysical scenarios, and their impacts on subsistence users. Module 4 details the socio-economic implications of these social impacts. Modules 2 and 4 can be omitted if there are no subsistence users. Many parts of DRIFT are now automated and the generation of hydrological data in the required RDM format has been incorporated into the hydrological software.

The main strengths of DRIFT are:

- it meets DWAF requirements in terms of outputs and the Ecological Reserve:
    - environmental flows are defined in terms of magnitude, duration, frequency and timing;
    - all recommended flows are motivated through consideration of the consequences for the river if they were not supplied;
- it quickly and easily produces any number of detailed scenarios once the database has been populated;
- large parts of the process are automated, with custom-built software;
- it can be used for regional planning, project planning, flow rehabilitation, defining flows to achieve a set objective or general river planning;
- it provides quantitative data on subsistence use of river resources;
- it can incorporate any relevant knowledge on the river;
- each scenario provides detailed predictions of ecosystem change that can be used for goal-setting in monitoring programmes;
- a comprehensive manual for its application is in preparation as part of a Water Research Commission-funded project (Southern Waters, in prep.);
- it produces, independently of the Desktop Model, any chosen number of scenarios linking class to an environmental flow requirement, which can be used to calibrate the Desktop Model;
- it can predict how river condition will be affected if the volume of water agreed for an environmental flows cannot be delivered in the required recommended temporal distribution, for instance, if large intra-annual floods cannot be released through a dam;
- all the responses from specialists are permanently recorded in the DRIFT database, making future manipulations (e.g. in response to new insights gained from monitoring) fairly straight-forward;
- it is objective and transparent – the early activities with the specialists do not focus on motivating for a specific flow regime, but on explaining the consequences of not providing different volumes and/or distribution of flows; the scenario-development phase, where volumes/distribution are linked to river condition, is a separate exercise, thus avoiding any pressure specialists may feel to recommend low volumes;

- it has been widely reviewed and recognised internationally.

Its weaknesses are:

- it is relatively complex to apply;
- there is a limit to how many flow-reduction levels the specialists may be able to describe the consequences of; these reduction levels may not match well with the levels needed when building scenarios;
- it is best suited to rivers with a fairly predictable flow regime.

6.3.3 Flow-Stressor-Response

FSR is designed to be used within an holistic method, and to date has been linked to the BBM. In the flow-assessment workshops, the major part of the BBM approach – that dealing with the setting of maintenance and drought low flows - is excised and the FSR is introduced in its place. It uses the same biophysical data and knowledge inputs as the BBM or DRIFT, to produce a description of how the river ecosystem responds in terms of biotic stress caused by reductions in the low flows. It is thus used at the scenario-building phase of an assessment, fulfilling the same kind of role as the low-flow components of Module 3 in DRIFT.

The description of river response to decreasing low flows is based on the assumption that hydraulic conditions in the river can be used as a surrogate for the degree of stress felt by aquatic communities. This stress is rated on a scale of 0 to 10, with least stress being linked to the highest low flows, and most stress to the lowest low flows. As flows are reduced, so are water levels and velocities, and many other physical and chemical variables are affected. This is assumed to be to the detriment of flow-dependent rheophilic (flow loving) aquatic species, whose stress levels will change relative to what they would have been under natural conditions. Each stress level for each species is thus linked to a specific range of discharges, and so a time series of daily flows can be transformed to a time series of stress levels, to show the magnitude, frequency and duration of any stress level for that species. From this, the magnitude, duration and frequency of different levels of stress can be derived. Additional time series, representing different flow scenarios, will produce different-shaped stress duration curves, which can be compared to each other and, above all, to the natural stress characteristics of the system. The desirability of any potential stress regime is judged by its deviation from the natural stress regime. The three main steps of the method are:

- using representative flow-loving species, the specialists apportion different ranges of low flow at the study sites to some or all of the stress levels 0 and 10;
- these stress levels are linked to several flow scenarios to produce stress time-series curves (i.e. the flow regime has been transformed to a stress regime);
- an EC category is assigned to each flow/stress scenario, based on the shape of its stress duration curve.

The strengths of FSR are:

- it meets DWAF requirements in terms of outputs for low flows for the Ecological Reserve:
    - low flows are defined in terms of magnitude, duration, frequency and timing;
- it quickly and easily produces any number of scenarios once the database has been populated;
- large parts of the process are automated, with custom-built software;
- it provides an indication of how river condition may change if the recommended temporal distribution of flows cannot be met;

Its weaknesses are:

- it focuses only on low flows, and so cannot be termed holistic.

6.3.4 Summary of the three approaches

DRIFT creates scenarios, indicates the EC category of each, and inputs all this into stakeholder meetings. The scenario eventually chosen by a decision-maker defines the Management Class for the river. This process should take place after full public consultation and consideration of the wider macro-economic implications. In other words, the desired river condition is not pre-determined, but emerges by consensus or political decision at the end of all deliberations.

The BBM defines different ecological states i.e. the EC categories, and recommends one. A flow regime is described to achieve this, and used to calibrate the model. Alternative scenarios are derived at the same workshop.

The FSR excises most of the BBM low-flow process and replaces this with FSR routines. The application of generic stress indices describes the pattern of stress in the original river condition and how this pattern changes with future flow scenarios.

In summary, all three approaches are designed, or have been developed in combination, to produce both a range of flow scenarios and the EC category of each.

6.4 Preparation of the hydrological data

The different approaches taken by the three methods become apparent at an early stage, when the hydrological data are prepared. A common thread still exists, however, as all distinguish between high flows (floods; freshes) and low flows (dry-season low flows; low flows between high-flow events). The BBM and DRIFT include both high and low flows in the assessment, whilst FSR addresses only the low flows and uses the DRIFT flood categories within a BBM framework to supply the high-flow recommendations.

6.4.1 The BBM

The BBM uses naturalised daily time series as well as present daily time series if available. If reliable daily data are not available, naturalised and present monthly data are used. The longest flow record available is used.

6.4.2 DRIFT

DRIFT uses measured or simulated daily time series of 20 or more years for each site. Where the present flow regime is markedly different from natural, it uses two simulated time series over the same time period: 1) natural, and 2) present. These are both analysed in the same way to gain an understanding of the present nature of the site. High flows are extracted from the hydrographs and allocated to one of eight size classes, using custom-built software:

- 1:20 year flood;
- 1:10 – 1:20 year flood;
- 1:5 – 1:10 year flood;
- 1:2 – 1:5 year flood;
- intra-annual flood Category IV (a magnitude range from just less than the 1:2 year flood to half that size);
- intra-annual flood III (top end of range is half the size of the top end of the Category IV range);
- intra-annual flood II (top end of range is half the size of the top end of the Category III range);
- intra-annual flood I (top end of range is half the size of the top end of the Category II range).

The remaining low-flows are allocated to any number of chosen seasons – usually a wet season and a dry season - and flow duration curves of each low-flow season illustrate the range of flows experienced in that season.

The resulting statistical descriptions of the flow components are used by the specialists to understand the distributions of species or channel features, and how these might change with flow changes.

The DRIFT software, developed by Ninham Shand and Southern Waters, through funds granted to Prof. A. Görgens by the Water Research Commission, partially automates all the above data manipulations.

6.4.3 FSR

The FSR has the same requirements as the BBM.

6.5 THE FLOW ASSESSMENT

In Steps 4 and 5 each approach incorporates one or more specialist workshops, in which the biophysical team uses all available data and understanding to advise on the links between flow regime and river condition. The following steps take place either during or after this/these workshop(s) (Figure 6.1).

6.5.1 Steps in the BBM assessment

For the recommended EC, the BBM process is as follows.

Setting a flow regime

1. The monthly flow requirements for low and high flows in maintenance and drought years (the Building Blocks) are given by the specialists.
2. The percentage assurance of the recommended maintenance flow regime is calculated.
3. Assurance rules are created for the recommended time series, to illustrate the flows that should appear at the site.
4. The specialists assess if the time series generated for maintenance and drought years are acceptable.

Scenario generation

1. The Desktop Model is calibrated using the flow data generated for the recommended EC, and used to identify the volume of water allocated to an EC one higher and one lower than the recommended EC. This volume-EC relationship only applies if the flows are distributed in the optimal pattern throughout the year, as indicated by the BBM recommended flows for the EC. For instance, if the recommended EC were a C, the Desktop Model would be used to generate a similar flow regime but with different volumes to maintain the river in a B or D category.
2. Assurance rules are created for each time series, to illustrate what flows should appear at the site.
3. Operational Scenarios can be included at this point, usually in a second workshop, where the specialists allocate to each scenario an EC and a description of the consequences for the river ecosystem.

6.5.2 Steps in the DRIFT assessment

In each place where reference is made to flow reduction, flow addition could equally apply.

1. The *range* of low flows in the wet and dry season are taken through up to four levels of reduction, and the specialists record how the river will change from present with each reduction. The reductions are considered in isolation, so that the sets of changes can be individually entered into a database and independently manipulated.

2. The *number* of intra-annual floods of each Flood Class is reduced up to four times, and the specialists record how the river will change from present with each reduction. Again, all the sets of changes are entered into the database.
3. The specialists record the ecological significance of the large floods, and the changes that would occur in their absence. Entered into database.
4. The volumes of water involved in each flow reduction are calculated, and also entered into the database linked to the relevant reduction level.
5. In discussion with management, a number of scenarios are agreed upon. Each scenario is created by selecting from the database the mix of high and low-flow reductions that match it most closely.
6. For each created scenario a time series with assurance rules is generated, and information on how the river will change from present. This provides specific measurables for a monitoring programme.
7. Each scenario is allocated to an EC.

6.5.3 Steps in the FSR assessment

The process for application of the FSR is as follows (O'Keeffe *et al.* 2002).

1. Selected sites of the study river are surveyed and described in terms of hydraulic habitat (depth, velocity, and wetted perimeter) at a range of discharges.
2. The generic-stress index is applied to each site by specialist ecologists, to develop stress curves for one, or typically more, critical flow-dependent species or groups. The curves describe the relationship between changing discharge and stress.
3. Where more than one stress curve is produced, these may be integrated to produce a single critical curve, based on the highest stress for any species/group at any discharge.
4. It may be appropriate to develop separate stress curves for different seasons because, for instance, the same magnitude discharge may have quite different stress implications during hot and cool seasons. In such a case, the curves should be used separately to produce seasonal stress profiles.
5. A specialist hydrologist uses the critical stress curve to convert the natural and any other flow time series (e.g. present day or other selected scenario) to a stress time series.
6. The resulting stress time-series are analysed as stress duration curves, or as spell analyses, to provide stress profiles which describe the magnitude, duration and frequency of stress levels experienced by the target organisms/components for the flow scenarios
7. The natural stress profile provides a reference against which to assess the relative changes in biophysical stress for the various flow scenarios.
8. Specialist ecologists assess the severity of the increases (or decreases) in stress, describe the ecological consequences, and rank the scenarios in terms of their impact. The aim of the ranking process is to identify the scenario for which the stress profile will impose the least differences in stress on the biota and habitats, compared to the natural stress regime.

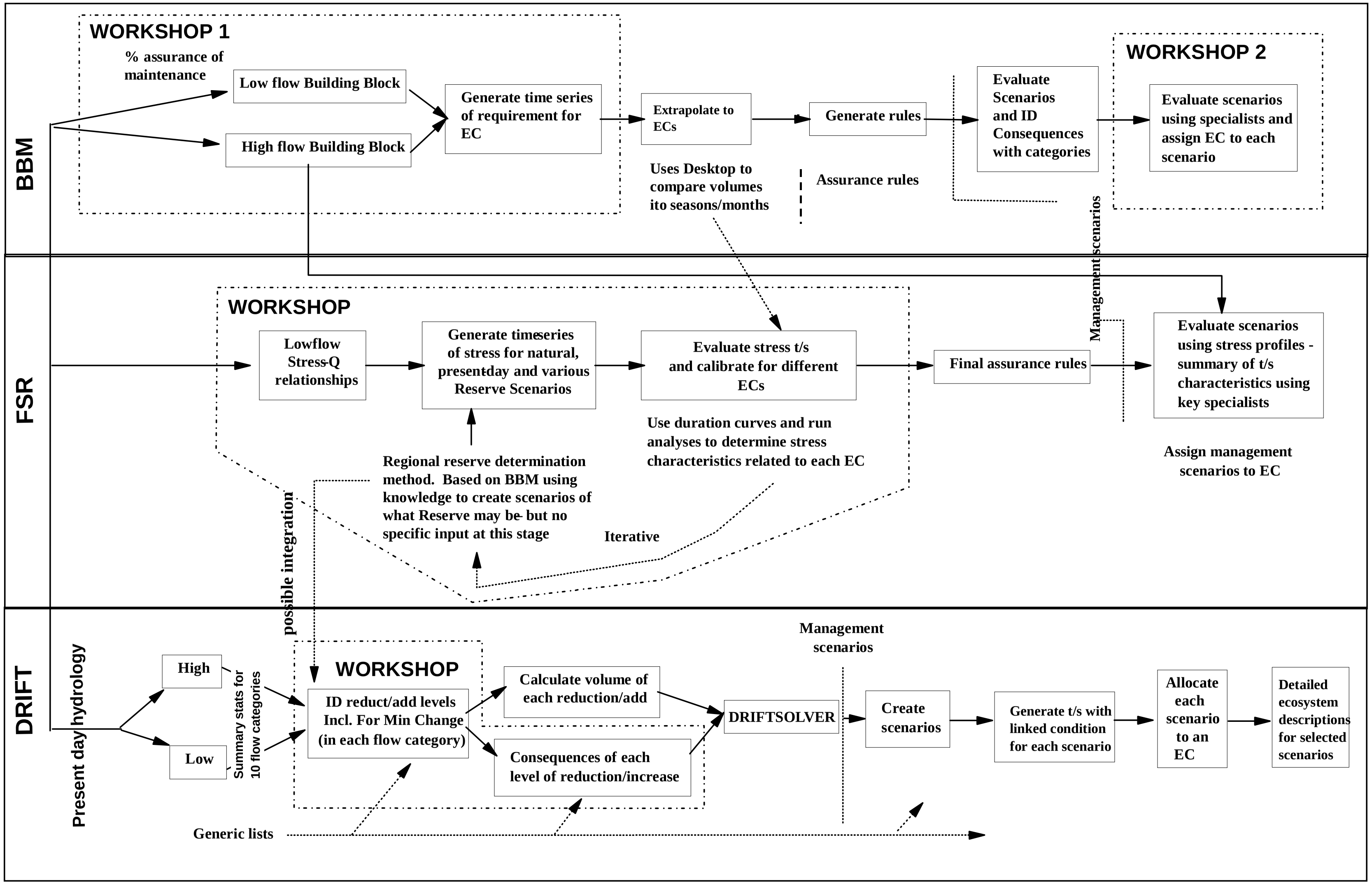

Figure 6.1 **Steps taken during specialist workshops**

6.6 The water-quality link

This will be reported fully in WRC Report No K5/1108 (Palmer *et al.* in prep).

6.7. Relative costs

A breakdown of the time required for data capture, collation and analysis for the BBM, DRIFT and FSR is detailed in Table 6.1. The time required is based on the following project scenario:

- 4 EWR sites in about 200 km stretch of main river.
- Travel time excluded.
- Disbursements excluded.
- Limited biological information available.
- Good daily hydrology available.
- Range of aerial photos available.
- River Quantity Ecological Reserve only.
- Inception phase excluded - time similar for each.
- Specialists include an ichthyologist, an invertebrate ecologist, a botanist, a geomorphologist, a hydrologist, a hydraulic modeller, a coordinator, facilitator and reporter. One of the specialists also does the habitat integrity assessments.
- Assume water-quality input comes from Quality Reserve.
- Ecoregional typing from DWAF.
- Habitat integrity - by helicopter.
- Three cross-sections per site.
- Subsistance use component not costed.
- Resource economics not included.
- BBM costs assume only three scenarios will be produced.
- No system analysis budgeted.
- Project management time is excluded as it would be similar for all three approaches.

Table 6.1 Breakdown of time requirements for application of the BBM, DRIFT and FSR. Note: the water-quality specialist is not included as methods are still evolving and thus time and personnel requirements not standardised. The costs would be identical for both BBM and DRIFT applications.

	BBM		DRIFT		FSR	
TASKS	**HOURS**	**DAYS**	**HOURS**	**DAYS**	**HOURS**	**DAYS**
1. MANAGEMENT						
Management	Not costed					
2. PLANNING MEETING						
Coordinator	8	1	8	1	8	1
Hydrology	8	1	8	1	8	1
Hydraulician	8	1	8	1	8	1

	BBM		DRIFT		FSR	
TASKS	**HOURS**	**DAYS**	**HOURS**	**DAYS**	**HOURS**	**DAYS**
Geomorphology	8	1	8	1	8	1
Vegetation	8	1	8	1	8	1
Fish	8	1	8	1	8	1
Aquatic macro-invertebrates	8	1	8	1	8	1
Facilitator	8	1	8	1	8	1
3. DELINEATE STUDY AREA & SELECT SITES						
3.1 Stream classification	16	2	16	2	16	2
3.2 Habitat Integrity						
Preparation	20	2.5	20	2.5	20	2.5
Flight	8	1	8	1	8	1
Analysis of data	32	4	32	4	32	4
3.3 Site selection*						
Coordination (incl. reporting)	24	3	24	3	24	3
Hydraulician	16	2	16	2	16	2
Geomorphology	16	2	16	2	16	2
Vegetation	16	2	16	2	16	2
Fish	16	2	16	2	16	2
Aquatic macro-invertebrates	16	2	16	2	16	2
4. DATA COLLECTION (EXCLUDING HYDRAULICS)						
4.1 Visit one						
Geomorphology			16	2		
Vegetation			32	4		
Fish			32	4		
Aquatic macro-invertebrates			16	2		
4.2 Visit two						
Vegetation			24	3		
Fish	16	2	16	2	16	2
Aquatic macro-invertebrates	8	1	16	2	8	1
Sediment transport modelling	16	2	16	2	16	2
5. DATA COLLECTION (HYDRAULICS, SURVEY, HABITAT MODEL)						
5.1. Survey						
Hydraulician /surveyor (2 days for 2 sites normal survey, 3 days for habitat model survey for 2 sites)	40	5	40	5	40	5
Geomorphology	16	2	16	2	16	2
Vegetation	16	2	16	2	16	2
5.2. Hydraulic calibrations (3 + site selection)						

	BBM		DRIFT		FSR	
TASKS	**HOURS**	**DAYS**	**HOURS**	**DAYS**	**HOURS**	**DAYS**
Hydraulician	48	6	48	6	48	6
Coordinator (photo-point monitoring)	48	6	48	6	48	6
6. ECOLOGICAL RESERVE CATEGORISATION						
6.1. Data analysis						
Geomorphology (aerial photo analysis)	16	2	16	2	16	2
Vegetation (aerial photo analysis)	16	2	16	2	16	2
Fish	16	2	16	2	16	2
Aquatic macro-invertebrates	16	2	16	2	16	2
Hydrology	16	2	16	2	16	2
Coordinator	16	2	16	2	16	2
6.2. Socio/cultural importance/subsistence use						
	Not costed					
6.3 Specialist meeting						
Coordinator	8	1	8	1	8	1
Hydrology	8	1	8	1	8	1
Geomorphology	8	1	8	1	8	1
Vegetation	8	1	8	1	8	1
Fish	8	1	8	1	8	1
Aquatic macro-invertebrates	8	1	8	1	8	1
Facilitator	8	1	8	1	8	1
Reporter (participation & reporting)	24	3	24	3	24	3
7. EWR DETERMINATION						
7.1 Data collation, analysis, reporting						
Coordinator	32	4	32	4	32	4
Hydrology	40	5	40	5	40	5
Hydraulics	80	10	80	10	88	11
Geomorphology	16	2	32	4	24	3
Vegetation	16	2	32	4	24	3
Fish	16	2	32	4	24	3
Aquatic macro-invertebrates	16	2	32	4	24	3
7.2 Specialist meeting						
Coordinator	24	3	24	3	16	2
Hydrology	24	3			16	2
Hydraulics	24	3	24	3	16	2
Geomorphology	24	3	24	3	16	2

	BBM		DRIFT		FSR	
TASKS	**HOURS**	**DAYS**	**HOURS**	**DAYS**	**HOURS**	**DAYS**
Vegetation	24	3	24	3	16	2
Fish	24	3	24	3	16	2
Aquatic macro-invertebrates	24	3	24	3	16	2
Facilitator	24	3	24	3	16	2
Reporter (participation & reporting)	80	10	72	9	80	10
Coordinator - post workshop analysis			8	1		
8. SCENARIO EVALUATION						
Coordinator	8	1	16	2	16	2
Hydrology	8	1			24	3
Hydraulics	8	1				
Geomorphology	8	1			2	0.25
Vegetation	8	1			2	0.25
Fish	8	1			2	0.25
Aquatic macro-invertebrates	8	1			2	0.25
Facilitator	8	1				
Reporter (participation & reporting)	16	2				
Grand total	1196	149.5	[1]1300	162.5	1140	142.5

[1] Additional data collection recommended (hence slightly higher costs) but not essential.

Table 6.1 reveals that the activities and time costs are very similar.

6.8 Comparison of outputs

The BBM and DRIFT were applied to three sites in the Breede River EWR study: Site 1 (Breede River at Mooiplaas), Site 2 (Molenaars River in Du Toit's Kloof and Site 4 (Lower Breede). The FSR was also applied to the first two sites, but the results are not reported on here. Outputs from the BBM and DRIFT applications can be compared in terms of total volume of water required for the environmental flow as a percentage of either naturalised or present-day volumes.

The process for the comparison at the level of percentage of MAR was as follows:

- the target long-term EC was noted from the BBM Report;
- the one detailed environmental flow regime for that site in the BBM Report was located – it described flows to meet the target EC (other scenarios are merely further flow regimes extrapolated from the original one using the Desktop model);
- the flow regime linked to the target EC was defined as a percentage of the naturalised and present-day MAR;
- of the three detailed and independent scenarios given for each site in the DRIFT outputs, that with same target EC as in the BBM document was selected;

- the selected DRIFT scenario had two entries for volumes required: with and without the inter-annual floods as the BBM and FSR assume these still pass down the system and so make no requirement for them;
- the DRIFT volume so identified was defined as a percentage of the naturalised and present-day MAR.

The results are shown in Table 6.2.

Table 6.2 Comparison of the percentage of MAR required as an environmental flow from BBM and DRIFT applications at three sites with different target conditions.

Site	Target EC	Annual volumes			% n MAR		
		BBM	DRIFT		BBM	DRIFT	
			I[1]	No I[2]		I	No I
Breede – Mooiplaas	D	102	169	116	30	49	34
Molenaars	B	79	82	66	50	53	41
Lower Breede	B/C	553	597	379	32	35	22

[1] values including inter-annual flood events.
[2] values excluding inter-annual flood events.

The difference between the DRIFT and BBM outputs (Table 6.2) appears to be linked to the way in which each deals with inter-annual floods. The low-flow requirements for each site (Figures 6.2-6.4) were much the same using both approaches, and the intra-annual flood requirement was identical, leaving the inter-annual floods as the only other major flow category that could be influencing the numbers. DRIFT explicitly includes all inter-annual flood requirements up to the length of the hydrological record used (usually about 20 years). The BBM explicitly includes all intra-annual floods but may or may not explicitly include the inter-annual floods. In the Breede application, they were excluded from the BBM application. The figures reveal that DRIFT required greater volumes of water in the wet season than did the BBM (Figures 6.2-6.4), but not in a consistent pattern. The causes of the inconsistency cannot be detected because the treatment of floods within the Desktop Model used to produce the BBM results is not amenable to analysis within this study.

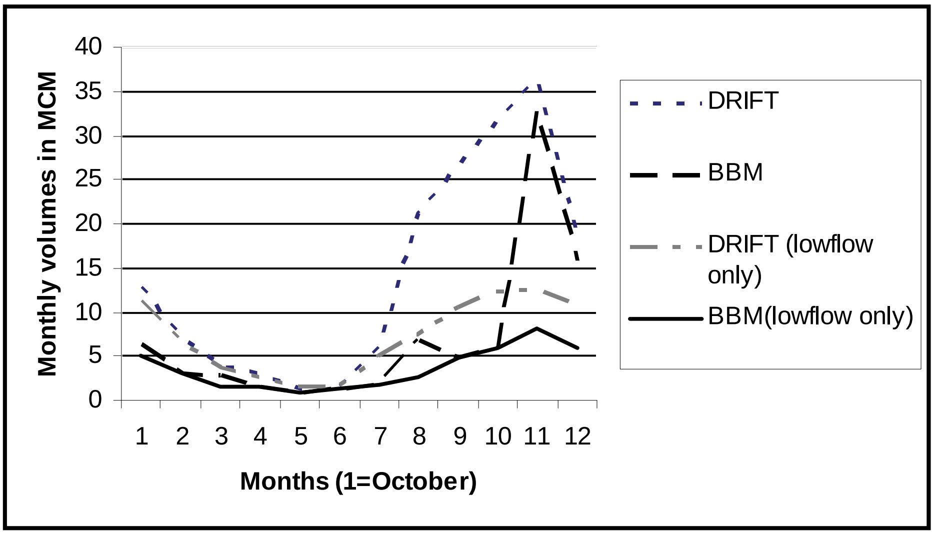

Figure 6.2 **BBM and DRIFT (inclusive of inter-annual flood requirements): monthly volumes for Site 1 on the Breede River.**

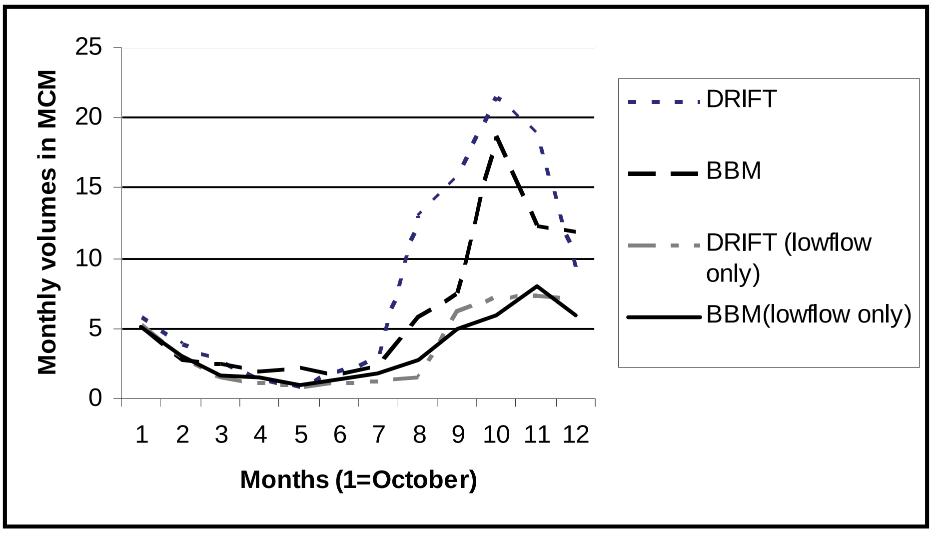

Figure 6.3 **BBM and DRIFT monthly volumes for Site 2 on the Breede River.**

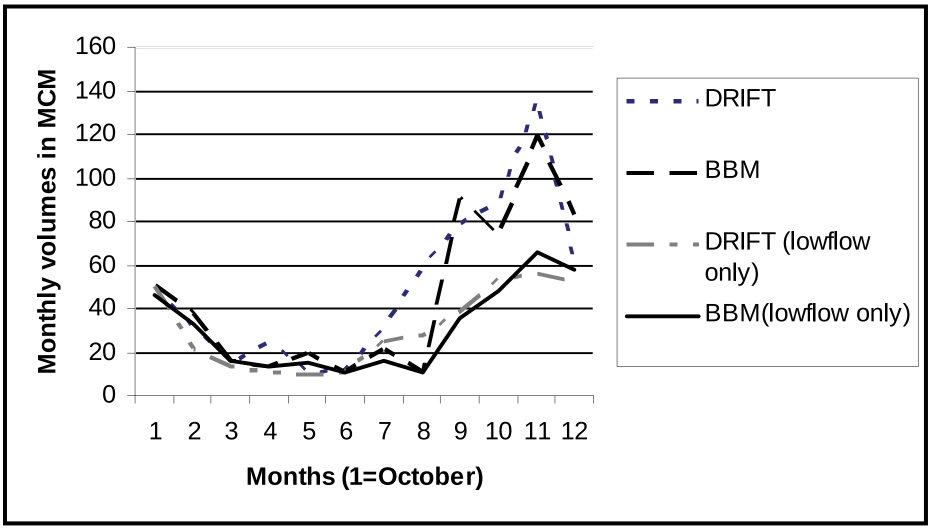

Figure 6.4 BBM and DRIFT monthly volumes for Site 4 on the Breede River.

The exception to the trend of both methods defining the same low-flow regimes was for Site 1, where the DRIFT low-flow requirement was higher than that for the BBM. At Site 1, the objective was to improve the expected river condition under the recommended EWR, and the two methods differed somewhat in terms of the recorded importance of wet-season low-flows for achieving this objective. To investigate this further, an additional DRIFT scenario was created for this site using the required low-flow levels from the BBM results. This revealed that the required D condition might have been possible, though it would more likely have been a D/E with a very high risk of a greater reduction in condition (Brown & King 2002c).

6.9 Compatibility of outputs with Reserve requirements

One of the important considerations with respect to integration of the three comprehensive Reserve determination methods is that they are all able to generate a common output that can be used in further water-resource analyses. The Water Resource Yield Model (WRYM) is in common use in South Africa for the determination of water-resource system yields, and has already incorporated a method for including Reserve demands. During recent Reserve determinations using the BBM it has become accepted that the output, for the purposes of yield impact assessments, is in the form of a table of flow volumes for each calendar month and for a range of assurances. These tables would normally include all the required Reserve flow elements (low flows and high flows) and represent an integration of the maintenance (or higher) and drought requirements in terms of the traditional BBM approach. However, it is also necessary in some circumstances to be able to generate the table with only the low-flow requirements (and possibly some of the smaller high flow events) represented. This situation might occur where the management options do not include control of high-flow releases.

Table 6.3 Example of a Reserve definition table

Summary of IFR rule curves for : Olifants IFR 1
Regional Type : Olifants
Ecological Category = C

Data are given in m^3 * 10^6 monthly flow volume

Month	% Points									
	10%	20%	30%	40%	50%	60%	70%	80%	90%	99%
Oct	1.432	1.420	1.395	1.343	1.246	1.085	0.859	0.598	0.375	0.272
Nov	2.949	2.932	2.896	2.825	2.692	2.459	2.090	1.576	1.003	0.643
Dec	4.445	4.418	4.363	4.253	4.048	3.690	3.120	2.328	1.445	0.890
Jan	8.794	8.041	7.380	6.765	6.126	5.052	4.256	3.152	1.920	1.145
Feb	13.475	12.058	10.836	9.737	7.530	5.740	4.940	4.100	2.431	1.335
Mar	5.251	4.861	4.515	4.185	3.831	3.233	2.750	2.079	1.331	0.861
Apr	1.994	1.980	1.951	1.889	1.774	1.585	1.318	1.010	0.747	0.625
May	1.234	1.227	1.212	1.181	1.123	1.027	0.891	0.735	0.602	0.530
Jun	0.949	0.944	0.933	0.910	0.868	0.798	0.699	0.586	0.489	0.430
Jul	0.907	0.903	0.892	0.869	0.827	0.757	0.659	0.546	0.450	0.405
Aug	0.835	0.830	0.819	0.796	0.753	0.682	0.583	0.468	0.370	0.325
Sep	0.737	0.732	0.721	0.699	0.657	0.588	0.490	0.377	0.281	0.210

The data contained within Table 6.3 are generated directly as part of the BBM or FSR methods where the Desktop Model is used to quantitatively define the Reserve requirements. These situations occur where the most reliable natural and present-day flow data are limited to time series of monthly volumes. In other situations, where reasonably representative daily flow data are available, it has been common practice to make use of the IFR model (Hughes *et al.* 1997) in the BBM, which is equally compatible with the FSR approach.

The approach within DRIFT is very similar to that when the IFR model is applied with the BBM and FSR approaches. The output from a DRIFT scenario is a time series of daily flows that represents the Reserve requirements for that scenario. This time series is reconstructed from the specifications (for a specific scenario) for each of the ten flow categories that form part of the DRIFT process. This daily time series can then be aggregated and duration curves generated in the same way as with the IFR model output. If a scenario is required that excludes some, or all, of the high flows then this can be achieved and a new duration table generated.

Thus, all three approaches can generate outputs that are compatible with the way in which the Reserve is currently dealt with within the WRYM. Additional work is currently being undertaken to develop simplified software that can be used to assess the impact of the Reserve on present-day water uses and future license applications in smaller catchments without major dams. In these situations the WRYM may not be appropriate and a quicker, more cost effective, solution may be frequently required. The developments being undertaken are based on the same common output (Table 6.3).

6.10 Comparison of the performances of the three approaches, using DWAF criteria

The criteria in Table 6.4 were provided by DWAF as part of the Terms of Reference for the BBM/DRIFT/FSR comparison exercise. Each of these is addressed in the light of the experience gained on the Breede River Basin Study.

Table 6.4 Comparison of key attributes of the three approaches

Attribute	**BBM**	**DRIFT**	**FSR**
<u>Process</u> Nature of process	Prescriptive	Interactive	Interactive
Degree of structure in process of knowledge capture, facilitating repeatability	Low	High	Medium
Designed to facilitate scenario assessment	No	Yes	Yes
Nature of specialists' inputs	Motivation for specific flows	Consequences of flow changes	Consequences of flow changes
<u>Hydrological input data</u> Uses whole flow regime	Yes, long-term data set used	Yes, long-term data set used	Addresses low flow only
Can use monthly hydro data	Yes but very low confidence	Designed for present-day daily data.	Yes but very low confidence
<u>Workshop characteristics</u> Structured organisation of data developed during workshop	Moderate	Rigorous	Moderate for low flows only
Database of flow-ecosystem responses for scenario development	No	Yes	No
Availability of supporting custom-built software	• hydro – yes • scenarios– no • database - no	• hydro – yes • scenario – yes • database - yes	• hydro – yes • scenario – developing • database - no
Allows quantity-quality integration	Yes	Yes	Yes
<u>Water quality</u> Can use monthly hydro data to prepare water quality component	Yes	Yes	Yes
WQ data requirements and use	Same		

Attribute	**BBM**	**DRIFT**	**FSR**
Can use monthly hydro data to produce water-quality scenarios	No	No	No
<u>Scenario development</u> Structured use of specialist knowledge in scenario creation/assessment	No	Yes	Yes
Can contribute to calibration of the Desktop Model	Yes (but can only use the recommended EC)	Yes	Yes
Degree to which magnitude, timing, frequency and duration of flows taken into account in scenarios	Low flows – low High flows - high	Low flows – high High flows – high	Low flows - high
Characteristics of outputs Repeatability of designated flow regime and linked river category	Dependent on knowledge and expertise of specialists and facilitator. BBM probably least repeatable due to lack of structured knowledge capture		
Results similar to other holistic approaches	Similar to DRIFT	Similar to BBM	-
Compatability with RDM Applicable at the Intermediate Reserve level	Yes	Yes	Yes
Production of Reserve tables	Yes	Can be done	N/A
Gives Resource Quality Objectives	Yes	Yes – in sufficient detail to become monitoring goals	Yes
Data output in terms of Reserve	Compatible	Compatible	Compatible
General Availability of skilled practitioners	Very low	Very low	Very low
Costs	Similar		

6.11 The way forward

This limited comparison of the three approaches has shown that DRIFT and BBM have similar costs and produce similar results. There would be a considerable advantage to maintaining dialogue between the groups developing FSR and DRIFT, and further examining the potential for integration. Some major considerations that should be addressed in further development are outlined below.

6.11.1 Establishing a logic trail

All environmental flow assessments are based on imperfect knowledge and understanding. It is therefore essential that the comprehensive methods (upon the outputs of which the rapid methods depend) have sufficient detail and a logic trail that allow analysis of any hydrological output and tracking of any prediction of flow change-ecosystem response. As new knowledge becomes available, it should be possible to amend the knowledge base and, from this, to amend the EF flow regime if necessary. In this way, the EF knowledge base becomes an implementation tool.

6.11.2 Developing the knowledge base

The specialists employed in the EF teams are being pushed to the limits of their knowledge and beyond. A quick and pertinent way to acquire new knowledge would be through structured and focused monitoring programmes of rivers with EFs. These programmes do not have to be large and expensive – the Kruger National Park Rivers Research Programme has outlined 'parsimonious' monitoring programmes (Rogers & Biggs 1999; Rogers e*t al.* 2000) that could play major roles in advancing understanding.

A suggested way forward is a four-pronged approach. First, complete comprehensive Reserve assessments in a limited number of important systems where time and funds can be dedicated to producing detailed results of high confidence. Second, support these assessments with directed research to enhance specialist predictions of change. Third, use the results of the comprehensive assessments to continue calibration of the Desktop Model so that it better reflects regional hydrological and ecological characteristics. The model could then be used in more of the routine Reserve determinations, reducing costs. Fourth, begin directed monitoring programmes on rivers with EFs to enhance the knowledge base and improve specialists' predictions of change.

It should be noted that because of the way scenarios are generated in the BBM (i.e. using the Desktop Model), each BBM assessment provides only one point for further calibration of the Desktop Model. This is the point provided by the BBM-derived flow regime for the recommended EC. All other scenarios created by the Desktop Model for that assessment are derived from the one recommended flow regime, using the relationships in the Desktop Model, and so cannot be used for further calibration. This highlights the need, if the Desktop Model is to become more sensitive to regional and other differences and more commonly used, for means to provide additional calibration points. Facilities such as the DRIFT database (DRIFT-SOLVER –

Chapter 3), and the FSR low-flow components, provide between four and ten points per assessment, all of which can be used in calibration.

6.11.3 Manuals and publications

A detailed manual exists for the BBM (King *et al.* 2000a). Although the method outlined in the manual for constructing flow regimes may not be used routinely now, the manual remains a source of very valuable information. There are chapters for each specialist discipline, detailing data-collection procedures, Terms of Reference and much more, which are relevant for all three methods. A manual is currently being written for DRIFT, along with instructions for the DRIFT hydrological software and the data templates (WRC project). The FSR software is in SPATSIM (Hughes & Forsythe 2002), but there is no manual as yet.

In terms of publications, the BBM is described in the international literature (King & Louw 1998) as well as in its manual. Aspects of DRIFT are described in two journals (Chapters 2 and 3), and in numerous international publications (e.g. Arthington *et al.* 2003; World Bank Technical Notes (Davies & Hirji 2003) and an IUCN guide for countries starting in this field (Dyson *et al.* 2003)). The FSR is described in the international literature (O'Keeffe *et al.* 2002), and notes on its use are included in SPATSIM.

South Africa is a generally seen as having done ground-breaking research in the field of EF assessments, and the literature forms an important part of recording both the history of this work and a means of exporting the science to other regions. Water managers and scientists from many countries seek links with this work, and it is suggested that South Africa should consider vigorous international marketing of its knowledge and skills in this field to exploit the demand.

6.11.4 River condition classes

Scenarios of river changes following flow changes can be summarised to indicate the expected river condition. Condition is expressed as a condition class, with a Class A river being a pristine one and a Class E/F river being severely degraded (DWAF 1999). In BBM/FSR applications, the future ecological state of the river under potential flow regimes is assessed by specialists without structured guidelines. Rules for this are presently being developed by Dr Kleynhans and his team at DWAF. In DRIFT, the scenarios emerging from DRIFT-SOLVER are allocated to condition categories guided by a detailed set of rules. At present, the class allocation when following these rules is a first estimate. The process needs to be tested in real monitoring programmes and refined.

Experience has shown that the condition classes are extremely useful to decision-makers. It is therefore strongly recommended that the above moves to standardise the process of class allocation be supported.

6.11.5 Challenges

Developing the technical tools to assess environmental flow needs has been a complex and difficult task. It probably is dwarfed, however, by the next challenge, that of implementation. River scientists now contribute to discussions on dam design, operating rules, licensing for water use, and basin planning. An important challenge for them is to develop a common understanding with, and be able to meet the relevant needs of, all DWAF directorates involved in natural-resource management. Communication among disciplines is not easy and takes time and personal commitment. Scientists can promote this process in many ways, such as through attendance and presentation at non-scientific conferences and meetings, searching for scientific solutions to management problems and, when scientific information is not being used, ascertaining why and how that can be changed.

6.12 Conclusions

The BBM, DRIFT and the FSR linked to BBM are all parts of a common process that is intended to result in the achievement of particular levels of resource protection for different rivers. They require similar input data and make use of all the steps in the Ecological Reserve, and provide outputs compatible with Reserve requirements. Their costs for a comprehensive assessment are comparable. DRIFT and the BBM are the more holistic, and of these DRIFT is the most complex but provides the greatest returns in terms of development of the knowledge base and guidance of monitoring. Differences between DRIFT and the BBM with regard to the flows for different classes of river can be as great as 10% of the MAR (Table 6.2), but not consistently so and not consistently with one higher than the other. The difference appears to be due to the way in which they deal with large floods in rule generation.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

DRIFT is an holistic EF assessment methodology that is in an advanced stage of development and still evolving. It has many valuable attributes including the following.

- A custom-build database that records, for all abiotic and biotic ecosystem components, the consequences of incremental changes in present-day flows.
- Hydrological software that transforms flow data sets into the form required for the database entries, and reconstructs modified flow regimes incorporating the incremental changes in flows.
- Generic lists, which structure entries into the database and themselves form the framework of an embryonic predictive ecological model.
- Software that uses the database to create scenarios of ecosystem change linked to any future flow change.
- Software that converts the predictions of ecosystem change to a river condition class, using clearly defined rules.
- A structured link between predictions of ecosystem change and predictions of impacts on subsistence users of the river.
- Scenarios in sufficient detail that the predictions of ecosystem change can be used directly as goals (RQOs – Resource Quality Objectives) for monitoring programmes.
- A user Manual, presently being written as a WRC project.

DRIFT meets all the requirements of the RDM (Resource Directed Measures) Directorate of DWAF in terms of outputs from a comprehensive assessment of the Ecological Reserve. It has approximately the same time and personnel costs as other methods presently used in Comprehensive Reserve determinations, with the added advantage that it contributes to a growing knowledge base through its detailed database of flow-ecosystem links for every river to which it is applied. The database also acts as an implementation tool, through its ability to quickly create many detailed scenarios of flow-change/ecosystem-response.

Other less obvious attributes are as follows.

- All the methods reported on in Chapter 6 assume an optimal distribution of high and low flows for any required volume of water. The DRIFT software also allows consideration of the consequences of less-than-optimal flow distributions; this is a common situation where dams cannot necessarily deliver all described EF flows. A specific volume of water, for instance, could lead to a B class river when flow distribution is optimal, but if intra-annual floods are trapped in an upstream dam and cannot be released downstream, the same volume of water without these floods could lead to, perhaps, a C class river. Outputs for either optimal or sub-optimal flow distributions can be selected in DRIFT and then automatically produce consequence descriptions and resulting river class.

- The BBM and FSR work from a starting point of the natural flow regime, as this is the regime that dictated the original nature of the ecosystem. By comparison, DRIFT uses the present-day flow regime as its starting point, as it has been found that the present condition of the river provides the specialists with their main understanding of the ecosystem. As the links to a measured flow regime become more tenuous, simulation, and importantly disaggregation into daily time series, of past (or future) flow regimes becomes potentially progressively more inaccurate. DRIFT's use of the present-day flow regime rather than an hypothetical pristine one helps reduce the chances of a site's hydrological data being inaccurate. This is important as it has long been recognised that if the hydrological and hydraulics data for an EF assessment are unreliable, then the whole assessment will be of very low confidence.
- The process whereby the specialists provide information on the consequences of flow changes is separated from that in which the scenarios are compiled. This means that the specialists can describe ecosystem responses without pressure to request more or less water (as could conceivably happen in BBM workshops). Separating the two processes ensures that the setting of scenarios is more objective.
- It is envisaged that the specialist information could perhaps be best acquired through an EF facilitator working individually with each specialist (in sequence from geomorphology to biota), rather than through an EF workshop. A short preliminary team meeting would still be required, as would some process whereby the specialists 'sign off' on each scenario eventually produced.
- Because the compilation of scenarios from the database and allocation of each to a river management class are automated, all through transparent rules, the same result is always obtained from the same input.
- DRIFT scenarios can be used to aid management at any time and spatial scale, from long-term Basin planning to single-site rehabilitation.
- New knowledge emanating from monitoring programmes can be used to amend database entries and generate updated scenarios. The DRIFT software thus acts as an implementation tool.
- DRIFT is amenable to incorporating, or being incorporated by, Bayesian networks, and to linkage with large-river fisheries models for use in developing countries with large floodplain fisheries. Both these applications are presently under investigation, via links with the Worldfish Center (CGIAR).

7.2 Recommendations

- Continue development of DRIFT and its knowledge base, through applications in comprehensive assessments of the Ecological Reserve. It is worth noting that it took about 15 applications of the BBM in real water-resource projects before it was felt that we had a method that worked and for which a manual could be written (Tharme & King 1998). To date, DRIFT has been applied three times (Palmiet River, Lesotho Highlands Water Project rivers and Breede River) and yet is already attracting wide international attention.

- Transfer the DRIFT database from Excel to a Delphi software package and further develop it, to provide the following features:
    - the database will be protected from being stolen and adjusted;
    - new data can be incorporated, and updated scenarios produced, without losing the original data;
    - generic-list items can be selected from drop-down lists;
    - incorporation of the DRIFT hydro software to form a single package;
    - a new format to ensure an attractive and user-friendly product;
- Develop further the database, to include the socio-economic aspect of DRIFT applications.
- Develop further the generic lists to provide lists that can be used in any South African river, and to explore their potential as the basis for an ecosystem model.
- Liaise with new DWAF work on river classes, and ensure compatibility with DRIFT river classes.
- Begin to explore the possibilities and limitations of applying DRIFT to other types of rivers, *viz*. ephemeral or intermittent systems and/or large flood plain rivers.

Finally, South Africa's expertise in the field of EF assessments is potentially highly marketable, as also is DRIFT. It is strongly suggested that the country act now to take advantage of this whilst other countries are still learning their way into this field.

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