ENVIRONMENTAL FLOW REQUIREMENTS OF FISH IN LESOTHO RIVERS USING THE DRIFT METHODOLOGY

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ABSTRACT

DRIFT (Downstream Response to Imposed Flow Transformations) is a scenario-based environmental flow assessment methodology applied during impact studies associated with the Lesotho Highlands Water Project, Southern Africa. DRIFT offers a structured process for predicting the biophysical, social and economic consequences of altering a river's flow regime. The fish component of DRIFT provides a ten-step protocol designed to make such predictions using field data on a river's fish fauna linked to information on flow-related aspects of fish biology drawn from the literature and the knowledge base and professional experience of fish ecologists. A worked example of the methodology is presented based on a study site downstream from Katse Dam on the Malibamatso River, Lesotho, where the ecological consequences of four flow scenarios were evaluated. DRIFT and its fish component have emerged from studies in a semi-arid, developing region where unpredictable hydrological regimes and data scarcity constrain the prediction of ecological responses to flow regulation. Faced with similar information constraints, scientific uncertainty and limited windows of opportunity to guide water management, other countries have employed scientific panels to recommend environmental flows. DRIFT and its fish component compare favourably with recommended best practice for Australian scientific panel assessments of the flow requirements of river ecosystems. The risks associated with use of scientific panel approaches are discussed and minimum data sets and standards are recommended for the conduct of a DRIFT fish assessment. DRIFT and related frameworks represent the second level in a three-tiered hierarchy of environmental flow methods. They can provide environmental flow recommendations of far greater scientific resolution than hydrological methods by integrating many types of information on the responses of riverine biota to flow modifications. However, DRIFT should only be applied within an adaptive management framework where there is a genuine commitment to the generation and use of new knowledge derived from monitoring and research. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS: environmental flows; DRIFT methodology; fish; best practice; Lesotho

INTRODUCTION

DRIFT (Downstream Response to Imposed Flow Transformations) is a scenario-based approach to environmental flow assessments developed by Southern Waters Ecological Research and Consulting Pty (Ltd) in liaison with SMEC (Snowy Mountains Engineering Corporation) International (Australia) and Metsi Consultants (an international team of biophysical river scientists). These groups were brought together to give advice on the flow requirements of rivers affected by the Lesotho Highlands Water Project, on behalf of the Lesotho Highlands Development Authority (LHDA). Earlier development of DRIFT in the Palmiet River, Western Cape (Brown *et al.*, 2000) and the Breede River, South Africa, set the scene for its refinement and application during environmental flow assessments in the montane catchments of Lesotho.

The DRIFT framework is made up of four modules, biophysical, sociological, scenario development and economic (Figure 1). Metsi Consultants (2000a) and King *et al.* (this issue) describe the DRIFT framework and the procedures constituting the biophysical module, as well as those used to determine the social and economic

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Figure 1. The four modules of the DRIFT framework showing the relationships between Module 1 (Biophysical, including the fish component of DRIFT), Module 2 (Sociological), Module 3 (Scenario Development) and Module 4 (Economic)

consequences of flow-related biophysical changes. This paper is concerned with the fish component of DRIFT, a set of procedures developed to assess the ecological consequences of flow regime change for the fish fauna of rivers in the Lesotho Highlands.

To make these assessments in any environmental flows study requires quantitative information on the relationship between river hydrology and key aspects of species biology (Pusey, 1998; Kennard *et al.*, 2000; Metsi Consultants, 2000b). The key information requirements are: species composition (at representative sites along the rivers to be affected by water infrastructure developments), habitat preferences and water quality tolerances of each species/developmental stage, patterns of movement and passage requirements, diet and foraging behaviour, reproductive biology, spawning habitats and larval/juvenile requirements (Figure 1).

Many environmental flow assessments involving fish proceed on the basis of only a fraction of this ideal knowledge base. Often, the minimum acceptable flow is based almost entirely on predictions of instream habitat availability matched against the habitat preferences of one or a few species of fish (Arthington and Pusey, 1993; Petts and Maddock, 1996; Jowett, 1997; Pusey, 1998) using hydraulic and habitat rating methods such as in-stream transect analysis and the habitat simulation modelling package PHABSIM (Bovee, 1982, 1986; Stalnaker *et al.*, 1994). Applications, strengths and limitations of PHABSIM are well-documented (King and Tharme, 1994; Stalnaker *et al.*, 1994; Pusey, 1998). A method linking the timing and magnitude of the low and high flow attributes of annual flow hydrographs to instream and out-of-channel physical habitat availability and suitability for fish was proposed by Hill *et al.* (1991), and there are more elaborate, data-hungry methods relating flow characteristics to the habitat, food and spawning requirements of fish. For example, O'Brien (1987) defined the minimum stream flow hydrograph to maintain existing habitat, food supply and spawning potential of the endangered Colorado River squawfish (*Ptychocheilus lucius*) in terms of four flow characteristics. To develop this minimum hydrograph, O'Brien (1987) combined the results of a two-year field study, a physical model, laboratory simulation of flows on cobble substrate and a mathematical simulation model of sediment transport. Williamson *et al.* (1993) developed a conceptual framework and a suite of interactive mathematical models of salmon production (SALMOD) simulating the dynamics of resident and anadromous freshwater populations.

The development of models equivalent to those applied to a single fish species by O'Brien (1987), or models such as SALMOD, in the remote and poorly studied rivers of the Lesotho Highlands was beyond the scope, budget and time frame (one year of field work and related studies) of the Lesotho environmental flows project. Furthermore, as an integral part of the DRIFT framework (King *et al.*, this issue), the fish component (like all biotic components) was required to conform to a range of generic features which existing methods such as PHABSIM and SALMOD cannot provide. The fish component had to: (i) consider the implications, for fish, of flow-related changes in channel morphology, sedimentary processes, physical habitat, water quality, and the spatial array, composition and diversity of aquatic invertebrates, aquatic macrophytes and riparian vegetation; (ii) evaluate the consequences (i.e. direction and severity) of many scenarios of flow change at multiple sites involving up to seven fish species; (iii) provide predictions about each fish species in formats that could be used by other ecologists (e.g. the wildlife ecologist needed information on the relative change in abundance of fish species that might be consumed by piscivorous birds); (iv) convert impacts of flow regime change on fish into social consequences for the people of Lesotho; (v) document the ecological basis of all predictions in structured, explicit and transparent formats, including predictions based on professional judgement; (vi) provide explicit confidence ratings for each prediction.

This paper describes the ten-step protocol forming the fish component of DRIFT and provides a worked example based on a study site downstream from Katse Dam on the Malibamatso River.

DRIFT has been developed in a semi-arid, developing region of southern Africa where unpredictable hydrological regimes and data scarcity can constrain scientific prediction of the ecological responses to flow regulation. In similar circumstances, other countries have also used scientific panel approaches to give advice on environmental flows. DRIFT and its fish component are compared with the recommended best practice for scientific panel assessments in Australia. The paper concludes with a discussion of the risks associated with such methods and suggests several ways to overcome them, ending on a precautionary note regarding the circumstances in which DRIFT and its fish component should be applied.

METHODS

Fish component of DRIFT

The basic steps in the fish component of DRIFT are the following:

- Step 1.* Review of literature to produce a compilation of published flow-related information on each fish species in the study rivers.
- Step 2.* Selection of study sites to characterize river reaches likely to be affected by existing and future water resource developments.
- Step 3.* Seasonal field surveys at each site to determine fish species composition, abundance and habitat use in relation to flow conditions.

- Step 4.* Analysis of field data to generate habitat preference curves for each fish species.
- Step 5.* Tabulation of field data and information from literature review to produce summary of flow-related data on each fish species.
- Step 6.* Development of scenarios of flow regime change for evaluation using DRIFT.
- Step 7.* Development of protocols to document the consequences of flow regime change for each fish species at each study site.
- Step 8.* Prediction of the ecological and social consequences of flow regime change for each fish species at each study site.
- Step 9.* Preparation of a monitoring strategy to assess the outcomes of environmental flow provisions.
- Step 10.* Implementation of monitoring programme, evaluation of ecological outcomes of any environmental flow provisions, and adjustment of those provisions in the light of new knowledge generated by monitoring (and research).

Steps 1–7 are described here (and in more detail in Metsi Consultants, 2000a,b). Step 8 represents the procedures involved in assessing the consequences of various scenarios of flow regime change, and as such is described in the worked example provided in the ‘Results’ section of this paper. Step 9, the monitoring strategy, is described in Metsi Consultants (2000b), and step 10 will be implemented in the next phase of the Lesotho environmental flows study.

Step 1. Review of literature to produce a compilation of published flow-related information on each fish species in the study rivers

The literature review involved preparation of a comprehensive report summarizing all information on the fish fauna of Lesotho rivers relevant to the core issues identified above and in Figure 1. This report documented species distributions in the study rivers, the habitat preferences and water quality tolerances of each species/developmental stage, patterns of movement, migration and passage requirements, diet composition and foraging behaviour, reproductive biology and phenology, spawning habitats and larval/juvenile requirements (Metsi Consultants, 2000b).

Step 2. Selection of study sites to characterize river reaches likely to be affected by existing and future water resource developments

The Kingdom of Lesotho is a small, high altitude mountainous country surrounded on all borders by South Africa. The region’s largest river, the Senqu River system, arises at high altitudes in Lesotho’s eastern highlands and flows into South Africa from the southwest of Lesotho (Figure 2). The Lesotho Highlands Water Project was conceived in the 1950s as a five-phase development beginning with Phase 1a, consisting of the 185 m high Katse Dam on the Malibamatso River, a hydropower scheme for Lesotho and associated infrastructure. Phase 1b included the 145 m Mohale Dam on the Senqunyane River and a 20 m Diversion Weir on the Matsoku River designed to divert water into Katse reservoir. Phases 2 to 5 would consist primarily of the Mashai Dam, the Tsoelike Dam, Ntoahae Dam and the Malatsi Dam on the Senqu River. If all of the proposed dams were to be built they would extend almost nose-to-tail along more than 300 km of Lesotho’s mountain rivers, with the harnessed water being pumped uphill to Katse reservoir for diversion into South Africa. In 1986, a treaty was signed between Lesotho and South Africa committing both countries to Phase 1 of the development. Katse Dam was completed in 1998 and first spilled that year; construction of Mohale Dam and Matsoku Weir began in 2000.

The study area for the environmental flow assessments undertaken using DRIFT included Lesotho rivers affected by Phases 1 and 2 of the Lesotho Highlands Water Project. Eight study sites were selected by Metsi Consultants to represent the geomorphological, hydrological and ecological characteristics of river reaches that may be affected by existing and future water resource developments on the Senqunyane and Senqu Rivers and their tributaries (Figure 2). Procedures for site selection followed those of the well-established Building Block Methodology (King and Louw, 1998; King *et al.*, 2000). Study site 2, downstream from Katse Dam on the Malibamatso River (Figure 2), is used throughout this paper to illustrate the fish component of the DRIFT methodology. This site was representative of the reach extending from Katse Dam to the Malibamatso and Matsoku confluence. Bank slopes at the site were moderate and the site consisted of a shallow pool, a deep pool and a riffle/rapid. The site was already modified by the presence of Katse Dam (completed in 1998 and spilling for the first time that year), most notably in that riparian vegetation had encroached onto previously bare sandbars.

Figure 2. Major rivers of the Lesotho Highlands, showing the location of Lesotho Highlands Water Project dams, transfer tunnels, and the study sites (including site 2 at Katse) where the DRIFT methodology was applied to environmental flow assessments

Step 3. Seasonal field surveys at each site to determine fish species composition, abundance and habitat use in relation to flow conditions

Field surveys were conducted at each study site in April, July and November 1998 and in January–February 1999. The data collected were fish species composition, abundance, habitat use of each species related to flow, and population size structure. The full range of meso- and microhabitats present at each site was sampled. Quantitative protocols described by Pusey *et al.* (2000) were used to record stream habitat characteristics (width, depth, velocity, substrate characteristics, instream cover and bank cover). Temperature, conductivity, dissolved oxygen and pH were also recorded at each site.

Fish were sampled using a variety of methods, including electrofishing, seine netting, gill netting and, occasionally, angling, with the choice of sampling methods depending on characteristics (particularly depth and velocity) of the sites. A portable back-pack electroshocker was the main sampling device used and electrofishing catches were standardized to catch-per-unit effort based on 60 minutes of sampling. Seine netting was also employed, where practicable, to collect any schooling species which electrofishing may have missed; usually three standard hauls were made with a 30 m long, 2 m deep seine net (9 mm stretched mesh). Occasionally, gill nets (a fleet of nine 10 m × 2 m panels with stretched mesh sizes of 24–120 mm) were set in deeper pools to assess the presence of large individuals, e.g. the rock catfish, *Austroglanis sclateri* (Niehaus *et al.*, 1997). Gill nets were deployed overnight for 12 hours and cleared periodically to prevent fish deaths.

All fish collected by electrofishing, seine netting and gill netting were identified to species, counted, measured (fork length, to the nearest millimetre) and returned alive to the water at the point of capture (except for the occasional individual inadvertently killed during capture). Samples of introduced rainbow trout were retained for analysis of diet and reproductive condition. Endangered species were never removed.

Methods used to collect fish microhabitat use data followed a protocol described in Kennard *et al.* (2000) combined with methods used by Niehaus *et al.* (1997). For each individual fish collected during electrofishing, the following data were estimated: mean water column velocity (portable flow meter), focal point velocity (portable flow meter), total water column depth (graduated stick), focal point depth (graduated stick), proportional substrate composition in 1 m² immediately below the fish (i.e. mud, sand, fine gravel, coarse gravel, small cobbles, large cobbles/boulders and bedrock), distance to nearest potential refuge (i.e. microhabitat structure), and distance to bank. For fish less than 0.2 m from the nearest refuge, we recorded the type of cover with which each fish was probably associated (i.e. filamentous algae, aquatic macrophytes, emergent aquatic vegetation, submerged stream bank vegetation, submerged overhanging stream bank vegetation, leaf litter, large woody debris, small woody debris, undercut banks and root masses, substrate and rocky undercuts).

Step 4. Analysis of field data to generate habitat preference curves for each fish species

Spearman's rank correlation analysis was used to investigate relationships between variations in fish abundance and instream habitat variables. Habitat use curves (Category II curves of Bovee, 1986) were developed for each fish species and developmental stage. Frequency distributions of depth, velocity, substrate and instream cover were generated from the fish habitat use information collected during electrofishing (pooled across all sites and sampling occasions). To ensure transferability of habitat use curves across sites with varying habitat structure, we standardized fish microhabitat use at each site in relation to habitat availability following the methods of Groshens and Orth (1994). For each species and developmental stage, habitat preference curves were produced from microhabitat data use and habitat availability data pooled from each site and sampling occasion. These data then reflected the relative degree of preference of each species for the range of instream habitat conditions available. Habitat suitability criteria were defined following Groshens and Orth (1994). Habitat suitability values >0.7 represented optimal conditions, values >0 to <0.7 were considered marginal and zero values represented unsuitable habitat.

Step 5. Tabulation of field data and information from literature review to produce a summary table of flow-related data on each fish species

This step involved the preparation of a summary of the flow-related ecological requirements of each fish species and developmental stage known or expected to occur at each study site (Table I). This data set provided the bulk of the biological information used to assess the consequences of modified flow regimes for the fish of Lesotho rivers. The fish team also had access to other ecological data (e.g. distributions of riparian and instream vegetation in relation to river stage and flow percentiles; composition and abundance of aquatic invertebrate communities associated with particular hydraulic habitats at each river site; and water quality data).

Step 6. Development of scenarios of flow regime change for evaluation using DRIFT

The biophysical assessments involved in the DRIFT methodology (Figure 1) were conducted during a multidisciplinary workshop held in the study area, taking a week to complete biophysical assessments for eight study sites. The workshop process began with the definition of scenarios of flow regime change based on hydrological analyses.

The DRIFT methodology takes as its starting point an analysis of the flow regime of the river based on historical and present-day daily time series flow data (spanning 20 years). Flows are separated into wet and dry season low flows, four classes of intra-annual floods and inter-annual floods with return periods of 1 in 2, 1 in 5, 1 in 10 and 1 in 20 years (Table II, Figure 3). Methods for distinguishing between these categories of flow are described in King *et al.* (in press). For the Lesotho study, these flow components were reduced in a structured manner (low flows were reduced in range and thus variability, and floods were reduced in number) to generate four flow scenarios (Metsi Consultants, 2000a).

- (1) *Minimum Degradation* was a hypothetical 'best case' scenario designed to maintain the rivers without measurable change from their present condition, accepting that Phase 1 and 2 dams are/will be in place. Most river flow would be left in the river to meet environmental requirements, with little water available for harvesting.

Table I. Summary of the biology and flow-related ecological requirements of fish species occurring in Lesotho Highlands rivers, including range of lengths for fish collected during this study, with maximum known size recorded in the literature given in parentheses. Microhabitat suitability criteria were obtained from habitat suitability curves weighted by habitat availability, or were derived from simple frequency of use curves (given in parentheses), see text for methods used. Cover variables are listed in decreasing order of importance

Fish species	Maloti minnow	Rock catfish	SM yellowfish	LM yellowfish	OR mudfish	R trout	Moggel	Chubbyhead
Fish length (cm fork length)	4.5–11.8 (13.0)	3.3–23.5 (30.0)	2.1–53.0	5.0–24.0 (82.5)	2.1–49.0 (50.0)	5.4–56.0 (122.0)	(50.0)	(12.0)
Microhabitat suitability criteria								
Adult								
Depth (m)	0.21–0.3 (0.07–0.6)	0.15–0.3 (0.15–3.0)	(0.6–2.7)	Moderate-deep	(0.3–1.71)	(0.4–2.5)	Moderate-deep	
Velocity (m/s)	0–0.1 (0–0.5)	0.6–0.8 (0–1.2)	(0–0.32)	Low-moderate	(0–0.09)	(0–0.28)	Zero-low	
Substrate	LC/B (S-Br)	LC-B (G-Br)	(S-LC/B)	Fine-moderate	(S-SC)	(S-LC/B)		
Cover	Subst/RockUC, LL, LWD, SWD, UC, RM, EV	Subst/RockUC, LL, SWD	Mac, Fa		Subs, LL, FA, MAC	Subst, LL, FA, MAC, SV		
Juvenile								
Depth (m)	(0.05–0.7)	(0.1–0.6)	(0.1–0.6)	Shallow-moderate	(0.15–0.60)	(0.11–0.30)	Shallow-moderate	
Velocity (m/s)	Glide-Backwater (FG-LC)	(0.14–0.89)	0–0.4	Moderate-high	(0–0.39)	(0.14–0.63)	Low-moderate	
Substrate		(LC/B)	M (S-LC/B)	Moderate-coarse	(M-LC/B)	(FG-LC/B)		
Cover			Subst/RockUC		Subs/RockUC	Subst/RockUC		
			SWD, LL, SV, FA, Ev		SV, LL, FA, MAC, SWD	EV, LL		
Passage requirements								
Minimum depth (m)	J = 0.07	J = 0.15	J = 0.08, A = 0.6		J = 0.1, A = 0.3	J = 0.08, A = 0.4		
Maximum velocity (m/s)	A = 1.61	A = 1.2	A = 1.37		J = 0.8, A = 1.36	J = 0.85, A = 1.65		
Reproductive requirements								
Spawning season	Oct.–Mar	Spring-early summer	Spring—mid-summer	Mid-late summer	Early spring-summer	Winter-early spring		Summer
Spawning migration			Upstream (Nov–Feb)		Lateral (during floods)		Upstream & lateral	
Spawning cues	Increased flows	Increased flows	Increased flood flows		Increased flows???		Increased flow	
Flows			70–140?			<20		
Magnitude (m ³ /s)								
Duration								
Frequency								
Timing								
			Spring (also later)			Winter-early spring		

Continues

Table 1. Continued

Temperature Incubation habitat requirements	14–22	> 18	> 18
Habitat type, sensitivity factors	Sensitive to siltation		In and off channel
Depth (m)	0.2–0.4		0.06–0.4
Velocity (m/s)	0.5–0.59		Moderate-high CG-B
Substrate	Coarse (CG-LC)	Moderate FG-CG	SV, OHV
Cover		CG-LC	SV, OHV, MAC
Temperature	14–22	18–21.5 3–8 days	1–3 days
Incubation duration at temperature given		2–3 days	4–7 weeks
Larval requirements			
Depth (m)	Sensitive to siltation (0.05–0.4)	Backwater pools (0.1–0.35)	Recruitment higher when spawning occurs on inundated floodplain habitats
Velocity (m/s)	Flat-Backwater (FG-CG)	0	CG
Substrate		C	
Temperature			
Larval development duration		Mobile 4–6 days	Mobile 3–4 days
Diet			
A	AI	Benthic O/D/A	Benthic D
		P	O
			Benthic D/A
			MO or AI
J	AI	Benthic O/D/A	AI/TI
L	MO	MO	MO
Other flow-related issues		High turbidity affects foraging	Cannot tolerate Temp >25, DO <3
			Juveniles undergo mass dispersal migrations

Key to codes: A—adult, J—juvenile, L—larvae.

Substrate characteristics: M—mud, S—sand, FG—fine gravel, CG—coarse gravel, SC—small cobbles, LC—large cobbles, Br—bedrock.

Cover types: Subst—substrate, RockUC—rocky undercuts, LL—leaf litter, LWD—large woody debris, SWD—small woody debris, UC—undercut banks, RM—root masses, MAC—aquatic macrophytes, FA—filamentous algae, EV—emergent veg., SV—submerged marginal veg., OHV—submerged overhanging veg.

Diet categories: O—omnivore, MO—microphagic omnivore, D—detritivore, A—algivore, AI—aquatic insectivore, TI—terrestrial insectivore, P—piscivore.

Table II. Statistical description of the flow regime at study site 2 (Katse) and the flow characteristics of four flow scenarios (from Metsi Consultants, 2000a)

Flow component	Discharge ($\text{m}^3 \text{s}^{-1}$)	Average number of events per year	Minimum degradation	Design limitation	Fourth scenario	Treaty
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
Intra-annual flood I	16–48	6	3	3	2	1
Intra-annual flood II	49–95	3	2	1	0.5	0
Intra-annual flood III	96–190	3	2	2	0.5	0
Intra-annual flood IV	191–379	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 environmental flow			66	33	18	4

P = present, A = absent.

*Dry season = June to November; wet season = December to May.

- (2) *Treaty* was a scenario that adhered to the minimal releases of the 1986 treaty signed between Lesotho and South Africa. It represented the opposite extreme from the Minimum Degradation scenario, with little water remaining in the river system and a maximum amount available for export.
- (3) *Design Limitation* was a scenario addressing the reality that, in terms of both dam-release structures and commitment to a moderate level of water delivery, there were limitations on the water that could be released downstream from dams already in place.
- (4) A fourth scenario was situated between the previous two in terms of the amount of water harvested versus that left in the river.

The flow components and scenarios evaluated at study site 2 (downstream from Katse Dam) are given in Table II. Under the possible Minimum Degradation scenario for site 2, the changes in flow regime would be: (i) the upper limit of the dry-season low flows reduced from the natural flow of 16 to $9 \text{ m}^3 \text{s}^{-1}$, and the upper limit of the wet-season low flows from 50 to $25 \text{ m}^3 \text{s}^{-1}$; (ii) for the intra-annual floods, three of the six Class I floods lost, one of the three Class II lost, one of the Class III lost, and one of the Class IV floods lost; (iii) all of the inter-annual floods would still occur except those with a five-year return interval; and (iv) 66% of the natural mean annual runoff (MAR) would remain in the river. At the other extreme of flow change, the Treaty scenario maximized water storage, with low flows remaining at a steady year-round dam release of 0.5 mm, all small to medium floods stored by Katse Dam, but on average one Class I flood generated per year by the downstream catchment, all large floods up to that with a 20-year return interval harvested by the dam, and only 4% of MAR left in the river. Scenarios (3) and (4) would provide intermediate levels of flow change, leaving 33% and 18% of MAR in the river (Metsi Consultants, 2000a).

Hydraulic models (e.g. a steady-state backwater model, Channel Flow Profile) were used to estimate the hydraulic characteristics (maximum depth, stream width, wetted area, wetted perimeter and mean velocity) of selected cross-sections at each study site (Metsi Consultants, 2000a). Table III presents the hydraulic data for one riffle/rapid and one pool cross-section at study site 2 (Katse), matching the flow data given for each scenario in Table II, plus data for the site during the April 1998 field trip (a benchmark situation familiar to all workshop participants). Figure 3a presents maximum depth, mean velocity and wetted perimeter in relation to discharge for the riffle/rapid cross-section at site 2, and Figure 3b depicts this cross-section showing the depth levels and ranges of wet and dry season low flows, the four classes of intra-annual floods and the four inter-annual floods.

These discharge and hydraulic data, plus information on channel geomorphology and sedimentary processes occurring at the discharges defining each flow scenario, as well as descriptions, maps and tabulated data representing hydraulic habitat structure (see King *et al.*, this issue), provided the physical basis for predicting the consequences of flow reductions for fish.

Figure 3. (a) Relationships of maximum depth, mean velocity and wetted perimeter to discharge for the riffle cross-section at site 2; (b) site 2 cross-section showing elevations of the four inter-annual floods (1 in 2, 1 in 5, 1 in 10 and 1 in 20 year recurrence intervals); (c) site 2 cross-section showing depth ranges of the Class I-IV intra-annual floods (left channel) and depth ranges of wet and dry season low flows (right channel). Table III explains these depths

Table III. Hydraulic data for study site 2 (below Katse Dam), derived for cross-section 2C (riffle) and cross-section 2B (pool) in relation to natural wet and dry season low flows, the Design Limitation scenario and during the April 1998 field trip

Hydraulic parameters	Natural wet season low flow (upper limit)	Natural wet season low flow (lower limit)	Natural dry season low flow (upper limit)	Natural dry season low flow (lower limit)	Design limitation dry season low flow (upper limit)	Discharge during April 1998 field trip
(a) Cross-section 2C (riffle)						
Q ($\text{m}^3 \text{s}^{-1}$)	50.0	0.07	16.0	0.05	1.9	9.1
Flow depth (m)	1.55	0.16	1.04	0.14	0.5	0.86
Width (m)	36.5	2.8	20.7	2.6	12.0	19.0
Area (m^2)	25.9	0.4	12.7	0.3	3.2	9.1
Perimeter (m)	38.4	2.9	22.1	2.8	12.6	20.2
Velocity (m s^{-1})	1.91	0.20	1.25	0.17	0.6	1.00
Cross-section 2B (pool)						
Q ($\text{m}^3 \text{s}^{-1}$)	50.0	0.07	16.0	0.05	1.9	9.1
Flow depth (m)	1.20	0.25	0.69	0.24	0.47	0.62
Width (m)	54.2	10.3	49.6	10.0	31.5	44.2
Area (m^2)	41.2	1.4	14.4	1.3	5.5	11.2
Perimeter (m)	54.4	10.3	49.7	10.0	31.5	44.3
Velocity (m s^{-1})	1.20	0.05	1.10	0.04	0.34	0.81

Step 7. Development of protocols to document the consequences of flow regime change for each fish species at each study site

The fish component of DRIFT was designed to predict the consequences of four types of flow reduction: loss of low flows during normally dry months; loss of low flows during normally wet months; loss of intra-annual floods; and loss of inter-annual floods with return periods of 1 in 2, 1 in 5, 1 in 10 and 1 in 20 years (Table II). Each change in a flow characteristic was evaluated separately in terms of the likely ecological (and social) consequences. DRIFT requires that these consequences are recorded on a proforma using a system of codes and ratings to summarize the following details: the issues affecting fish when low river flows and floods are reduced; their possible effects on fish individuals, populations and species interactions; the direction and severity of the ecological consequences of each flow alteration; the overall consequences for the river ecosystem; and the level of confidence in the ecological assessment. The possible social consequences of changes in fish diversity and abundance at each site were also evaluated. Each of these steps is explained below.

Two generic lists present the flow-related issues affecting fish: Table IV (ecological requirements of fish likely to be affected by reduction in low flows) and Table V (ecological requirements of fish likely to be affected by reduction in intra- and inter-annual floods). Table VI lists the possible effects of flow regime change on fish at the level of individuals, populations and species interactions. The ultimate ecological consequence of flow regime change was considered to be the loss of one or more species of fish from a site and the river zone it represented. These generic issues were identified from the literature and our collective experience as river ecologists and participants in environmental flow studies in Australia and South Africa (Junk *et al.*, 1989; Poff and Ward, 1989; Arthington *et al.*, 1992, 1998, 2000; Gordon *et al.*, 1992; Arthington and Pusey, 1993; Skelton, 1993; Walker and Thoms, 1993; Petts and Maddock, 1994; Gehrke *et al.*, 1995; Pusey *et al.*, 1995a,b, 1998a,b, 2000, 2001a,b; Ward and Standford, 1995; Richter *et al.*, 1996, 1997; Arthington and Long, 1997; Jowett, 1997; Niehaus *et al.*, 1997; Poff *et al.*, 1997; Arthington, 1998; Arthington and Lloyd, 1998; Arthington and Zalucki, 1998; King and Louw, 1998; King *et al.*, 1998; Puckridge *et al.*, 1998; Pusey, 1998, 2001; Rall, 1999; Brizga, 2000; Kennard, 2000; Kennard *et al.*, 2000; Bunn and Arthington, 2002).

When evaluating the Minimum Degradation scenario flows and responding to other flow scenarios, it was decided to place emphasis on the requirements of the most sensitive fish species present at each site, usually a species of high conservation significance (Table VII). For Minimum Degradation, a sensitive species should be able to persist at the study site without measurable change in the abundance of any life history stage likely to

Table IV. Ecological requirements of fish likely to be affected as low flows are progressively reduced in range and thus variability

Issue code	Low flow issues
1	Suitability of adult habitat (depth, velocity, substrate, cover, wetted perimeter)
2	Suitability of juvenile habitat (depth, velocity, substrate, cover, wetted perimeter)
3	Suitability of larval habitat (depth, velocity, substrate, cover, wetted perimeter)
4	Suitability of habitat for fish passage of:
a	Adults
b	Juveniles
c	Larvae
5	Availability of refuge habitat for adult fish
6	Availability of spawning and egg incubation habitat
7	Water temperature
8	Rate of fine sediment accumulation in interstitial spaces of coarse substrates
9	Abundance of epiphytic algae
10	Amount of suspended colloidal matter in low flow areas
11	Pool depth
12	Abundance of aquatic invertebrates
13	Aquatic invertebrate assemblage composition (e.g. predators versus filter feeders versus detritivores)
14	Rate of input of allochthonous food resources (terrestrial insects, fruit, flowers)
15	Nutrient levels and primary production
16	Dissolved oxygen levels
17	Turbidity levels (due to livestock trampling at river margins)
18	Presence of toxic algal blooms

Table V. Ecological requirements of fish likely to be affected as intra- and inter-annual floods are progressively removed from the flow regime

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
6a	Availability of spawning habitat
b	Quality of spawning habitat
7	Maintenance of interstitial spaces utilized 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 macrochannel 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

be present in the wet or dry season, and preferably, all other species must also be able to persist without measurable change. The social consequences of the Minimum Degradation scenario should be that there is no change in the usual number of fish species caught by local people using their traditional fishing methods (baited lines), nor any measurable change in the numbers caught, the body size ranges or the nutritional value of the fish. The social values of each fish species are given in Table VIII, those of highest value to Basotho people being easily caught and an important food resource.

The direction of the effect of each change in a flow component was assessed as positive (an increase in fish numbers), zero (no change in fish numbers) or negative (decrease in fish numbers). The relative severity of the

Table VI. Effects of flow regime change on fish individuals, populations and species interactions

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 adult fish
D	Change in abundance of juvenile fish
E	Change in abundance of larval fish
F	Change in spawning and hatching success
G	Change in level of passage and dispersal for: (i) Adults (ii) Juveniles (iii) Larvae
H	Change in predation level
I	Change in competitive pressure
J	Change in mortality levels
K	Loss of species from site

Table VII. Fish species of high conservation significance (1996 IUCN Red List) present in Lesotho rivers, presumed also to be the most sensitive

Fish species	Conservation status
Rock catfish (<i>Austroglanis sclateri</i>)	Presently listed as Data Deficient, previously Red Data Species (endangered)
Largemouth yellowfish (<i>Labeobarbus kimberleyensis</i>)	Red Data Species (vulnerable)
Maloti minnow (<i>Pseudobarbus quathlambae</i>)	Red Data Species (critically endangered)

Table VIII. Fish species expected in Lesotho rivers and their social values for the Basotho people

Fish species	Fish social values
Rock catfish (<i>A. sclateri</i>)	Easy to catch Important food resource Commonly caught and utilized
Smallmouth yellowfish (<i>Labeobarbus aeneus</i>)	Easy to catch Important food resource Commonly caught and utilized
Largemouth yellowfish (<i>Labeobarbus kimberleyensis</i>)	Easy to catch Important food resource Not commonly caught, less utilized
Orange River mudfish (<i>Labeo capensis</i>)	Hard to catch Potential food resource Not commonly caught, less utilized
Trout (<i>Onchorhynchus mykiss</i>)	Easy to catch Important food resource Commonly caught and utilized
Sharptooth catfish (<i>Clarias gariepinus</i>)	Easy to catch Potential food resource Not commonly caught At limit of distribution range
Moggel (<i>Labeo umbratus</i>)	Easy to catch Potential food resource Not commonly caught At limit of distribution range
Maloti minnow (<i>Pseudobarbus quathlambae</i>)	Hard to catch Not commonly caught, not utilized

effect of each water level reduction on each fish species was determined using criteria given in Table IX. The overall ecosystem significance of each flow regulation scenario was rated independently from the social consequences. For fish, an impact rating of 5 was assigned in every circumstance where one or more Red Data species (see Table VII) was collected at a study site and therefore could potentially be reduced in abundance or eliminated from

Table IX. Severity rating criteria for assessing the effects of flow reduction on fish

Severity rating	Criteria	Consequence
0	All ecological requirements are met	No change in species abundance
1	Most ecological requirements are met	Negligible change in species abundance
2	Some ecological requirements are met	Small change in species abundance
3	Few ecological requirements are met	Moderate change in species abundance
4	Very few ecological requirements are met	Severe change in species abundance
5	No ecological requirements are met	Loss of a species

Table X. Social consequences and ratings describing the effects of flow regulation on fishing potential

Rating	Consequence	Change in fishing success (%)
0	Fishing success maintained as normal	0–5
I	Negligible change in fishing success	6–10
II	Fishing success slightly reduced	11–25
III	Fishing success moderately reduced	26–50
IV	Fishing success severely reduced	51–80
V	Fishing success very severely reduced or no fishing success	81–100

the site by flow regulation. A rating of 4 was assigned when one or more Red Data species was expected at a study site based on the known distribution of the species but not actually sampled during the present study. The rationale for these high ecosystem ratings was that Red Data species are extremely important from a conservation perspective and any further pressure on populations could, in the long term, result in the loss of those species from a river reach or entire tributary. Such losses can be of utmost importance when a species has a very restricted distribution and exists primarily as small isolated populations, as does the Maloti minnow (Rall, 1999) for example.

Confidence ratings assigned by the fish team were: high (H) = supporting data extensive, underpinned by peer-reviewed papers and reports on each fish species; moderate (M) = supporting data less extensive, underpinned by peer-reviewed papers and reports on some fish species, unpublished data and direct observations in the study rivers; and low (L) = predictions based on anecdotal information, personal experience and best professional judgment.

The direction/severity ratings assigned to the ecological consequences of each water level reduction were converted to social consequence ratings. Table X gives numeric ratings proposed by the fish team to reflect possible levels of change in fishing success, where 'success' was evaluated in terms of the traditional fishing methods used by the Basotho people (i.e. baited lines). Note that a numeric increase in the abundance of Orange River mudfish (which usually responds positively to flow reductions) was not translated into a high, positive social consequence rating because the mudfish is relatively difficult to catch and usually does not constitute a large part of the diet of local people (Table VIII). The mudfish is a benthic algivore/detritivore and therefore does not take bait readily, if at all.

DESCRIPTION AND RESULTS FROM A WORKED EXAMPLE OF THE FISH COMPONENT OF DRIFT

Steps 1–7 of the fish component of DRIFT have been described above. Here we present the procedures involved in, and a worked example of, Step 8 (prediction of the ecological and social consequences of flow regime change for each fish species at each study site). We use study site 2 downstream from Katse Dam to demonstrate the fish assessment methods.

Four fish species were collected at site 2 over the four sampling occasions between April 1998–early 1999 (Table I). These were the endangered rock catfish (*Austroglanis sclateri*), the smallmouth yellowfish (*Labeobarbus aeneus*), Orange River mudfish (*Labeo capensis*) and introduced rainbow trout (*Onchorhynchus mykiss*). Although not caught during surveys, largemouth yellowfish (*Labeobarbus kimberleyensis*) could be expected at this site,

being present in this part of the river system (J. Rall, personal communication, 2001). Length frequency histograms for each fish species indicated that the riffle/rapid and the shallow pool at site 2 were utilized only by smaller size classes of each species (<10 cm fork length), such pools probably serving as nursery areas for developing young-of-the-year fish. The larger size classes of all species were collected in the deep pool at site 2, suggesting that this was an important refuge area for adult fish. Introduced rainbow trout were not given a high priority in our assessments owing to their potential negative effects on indigenous fish species; however, the consequences of flow alternations for trout were recorded, and could be rated as positive (desirable food resource for people) or negative (pest species) in socio-economic evaluations, if so desired.

Four flow scenarios were evaluated: Minimum Degradation, Treaty, Design Limitation and a fourth scenario (described above in Step 6). The changes in flow regime (reduction levels) for each flow scenario are given in Table II with the matching hydraulic data summarized in Table III. The evaluation procedure has several steps described and documented below.

Step 8a. Establish Minimum Degradation level for low flows in dry months

Determination of the Minimum Degradation scenario was an iterative process involving all workshop participants in progressive evaluations of water levels and associated river features until agreement was reached on a flow 'having a minimal impact on present river condition' (King *et al.*, this issue). The Minimum Degradation scenario agreed at the Lesotho workshop for study site 2 (Katse) resulted in an upper limit of dry season low flows of $9.0 \text{ m}^3 \text{ s}^{-1}$, a maximum water depth of 0.86 m and mean velocity of 1 m s^{-1} . Here we demonstrate how this scenario would meet the requirements of fish collected at the site or expected there (Table I).

The most sensitive species at site 2, the rock catfish, was evaluated first, followed by the other species collected and expected. Data collected during the Lesotho study on habitat use of the rock catfish confirmed published reports that rock catfish live in rocky habitats in flowing water, favouring rapids (Skelton, 1993). In the Lesotho rivers surveyed, catfish abundance was significantly correlated (Spearman's rank correlation, $p < 0.05$) with mean stream width, mean water velocity, presence of large cobble/boulder substrates and rocky undercuts, and negatively correlated with sandy substrates, indicating that this species was more abundant in wide, high gradient streams (Metsi Consultants, 2000b). Catfish were also more common in hydraulic habitats containing aquatic macrophytes and submerged overhanging vegetation. Information about the rock catfish assembled from field surveys and the literature is given in Table I.

Evaluation of the Minimum Degradation scenario began with selection of cross-sections closest to the hydraulic habitat types surveyed during field studies. At site 2, the cross-sections selected were 2C (riffle/glide) and 2B (pool) (Figure 3). Starting with the riffle/glide cross-section, we determined the suitability of the habitat available when the natural flow would be at the upper limit of the dry season (June to November) low flows (i.e. the 1 percentile exceedence flow water level) using the hydraulic data given in Table III. The depth and velocity preferences of each fish species/developmental stage at this site (Table I) were compared with the tabulated hydraulic data.

The preferred depth range for adult rock catfish was found to be 0.15–0.3 m, and for juveniles 0.1–0.6 m; the preferred velocity range for adults was $0.6\text{--}0.8 \text{ m s}^{-1}$, and for juveniles $0.14\text{--}0.89 \text{ m s}^{-1}$ (Table I). Field surveys of hydraulic habitat in the riffles/glide at a range of discharges over one year (data collected by geomorphologist, fish and invertebrate ecologists) showed that adult and juvenile catfish substrate requirements and cover preferences would be met at the riffle/rapids cross-section when flow depths were up to 0.86 m. The minimum depth required for adult rock catfish to ensure passage is not known but juveniles move in depths of 0.15 m, well within the depth range available at the Minimum Degradation discharge (maximum of 0.86 m). Maximum velocities for juveniles to make passage are not known but adult catfish tolerate up to 1.2 m s^{-1} , and their movements would not be constrained by Minimum Degradation velocities at the site 2 riffle/rapid. There were two rocky trenches at the riffle/rapid (Figure 3) within which catfish would be able to find resting areas under rock outcrops and boulders, and through which they should be able to pass to reach pool habitats upstream. We concluded that adult and juvenile habitat and passage requirements of rock catfish (and the other species present, evaluated as described here) would be met by the Minimum Degradation scenario low flows through the riffle/rapid during the dry season.

Following the assessment of the consequences of a possible Minimum Degradation level for fish at the riffle/glide, the implications of this discharge were considered in pools. This evaluation was focused on the functional

importance of pool habitat in relation to the ecological requirements of rock catfish and other fish species inhabiting site 2 (Table I). Larger individuals of rock catfish (and of smallmouth yellowfish, mudfish and trout) were collected using gill nets in the deeper pool at site 2, suggesting that this habitat was an important refuge for adult fish of all four species. This habitat may be particularly important for the rock catfish and largemouth yellowfish (not collected but expected at this site), both being species of high conservation significance. Depths, velocities and substrates in the site 2 pool were suitable for rock catfish adults and juveniles, both pools having areas of bedrock, boulders and cobbles favoured by this species.

Rock catfish are omnivorous, preying on aquatic invertebrates, primarily insect larvae and nymphs taken from rock surfaces; larger specimens also take small fish (Skelton, 1993). These food resources were readily available in the riffle/glide and pools areas at site 2, where potential prey species (smallmouth yellowfish and Orange River mudfish) were relatively abundant (CPUE based on 60 minutes of electrofishing) on all sampling occasions over one year (Metsi Consultants, 2000b) and the benthic invertebrate fauna was diverse.

Rock catfish probably spawn in spring and early summer, possibly in response to increasing discharge, therefore spawning requirements may not be an issue during the cooler, dry season low-flow period, but rather, at the start of the wet season when rising water temperatures, somewhat elevated low flows and within-channel floods may provide spawning cues. All indications are that this catfish spawns over cobbles and rocks in flowing water, whereas new recruits are found in backwater pools (R. A. Jubb, Albany Museum, Grahamstown, South Africa, unpublished report, 1970; Niehaus *et al.*, 1997). We concluded that if spawning does sometimes occur during the latter part of the low flow period, the habitat conditions at site 2 would be suitable for incubation of the eggs, larval development and feeding, and the movement of new recruits into pool areas (*cf.* details in Table I).

Step 8b. Evaluate flow reductions below Minimum Degradation low flow level

The specific ecological consequences for each fish species resulting from the three progressive reductions in low flow water levels were evaluated using the methods outlined above. With each of these flow reductions (Design Limitation, fourth scenario and Treaty; see Tables II and III), rock catfish populations would be expected to decline progressively due to loss of low flow habitat for adult and juvenile fish, especially in shallow riffles and glides, reduced opportunities to make passage, decline of the preferred food resources (invertebrates on rock surfaces would be exposed frequently at very low flows), and possibly, decline in water quality (e.g. decreased dissolved oxygen concentrations), particularly in deeper pools. Any increase in turbidity at low flows could affect visually orienting piscivores such as the yellowfish (Cambray, 1984) and possibly also the rock catfish. If catfish spawning were to occur, the infilling of interstitial spaces in cobble substrates due to increasing settlement of colloidal material, sediment and small particles at low flows, as well as buildup of biofilms (Metsi Consultants, 2000a), could lead to suffocation of eggs.

Table XI provides the proforma data entries recording the ecological consequences of low flow reduction at site 2 for the Design Limitation scenario. A proforma of this type was completed for each low flow reduction level, and the four proformas, the graphic and tabulated data describing hydraulic conditions at each cross-section and a site-specific version of Table I (indicating the fish species and life history stages evaluated) were all submitted to the workshop convener for input to a customized database and for use during socio-economic evaluations.

Step 8c. Establish Minimum Degradation level for low flows in wet months

Step 8d. Evaluate flow reductions below Minimum Degradation low flow level in wet months

Identical procedures were employed to agree upon Minimum Degradation flows and evaluate the consequences of low flow reductions in wet months of the year, that is, those intervals between floods when low flows are higher than during dry months. The particular issues of most relevance to fish at site 2 were identical to those given in Table XI except that more emphasis was given to the reproductive requirements of catfish and other species which commence to spawn during the early wet season (Table I). For Design Limitation (see Tables II and III), we concluded that the ecological consequences of loss of low flows during the wet season should be rated 4 = very few ecological requirements met, severe change in species abundance expected (Table IX).

Table XI. Fish consequence summary for Design Limitation scenario dry season low flows at study site 2 (Katse)

Study site number: 2	Site name: Katse	Specialists: AA, JR, MK	
Low flow season: Dry	Component: Fish		
Flow scenario: Design limitation			
Discharge range for scenario and component: 0.05–1.9 m ³ s ^{−1}			
Ecosystem significance rating: 5*			
Generic list of ecological issues affecting fish at site:			
Issue	Species	Explanation of consequences	Rating
1, 2, 4a,b, 5 8–13, 16–18	Rock catfish*	A–D, G, H–J Social IV	Direction: –ve Quantity/severity: 4 Confidence: medium
1, 2, 4a,b, 8–13, 16–18	Smy Lmy*	A–C, G, H, J Social IV	Direction: –ve Quantity/Severity: 4 Confidence: medium
1, 2, 8–13, 16–18	Orm	A–C, G, H, J Social 0	Direction: +ve Quantity/Severity: 2 Confidence: medium
1–6, 8–13, 16–18	Trout	A–G Social IV	Direction: –ve Quantity/Severity: 4 Confidence: medium

Specialists: AA = Angela Arthington, JR = Johan Rall, MK = Mark Kennard.

Ecosystem significance rating 5*: rock catfish and largemouth yellowfish are Red Data species (see Table VII).

Issue: 1 = suitability of adult habitat (depth, velocity, substrate, cover, wetted perimeter (see Table IV)).

Species: Smy = smallmouth yellowfish, Lmy = largemouth yellowfish, Orm = Orange River mudfish.

Consequences: A = change in fish health (due to effects of disease, parasites, toxic algae, etc.) (see Table VI).

Direction: +ve = increase in abundance of Orange River mudfish as low flows are reduced, but social value 0 as mudfish are difficult to catch and seldom eaten by Basotho people (see Table VIII).

Quantity/Severity: 4 = very few ecological requirements met, severe change in species abundance expected (see Table IX).

Social: IV = fishing success severely reduced, % change 51–80 (see Table X).

Step 8e. Establish Minimum Degradation level for intra-annual floods

Step 8f. Evaluate reduction scenarios below Minimum Degradation for intra-annual floods

Step 8g. Establish Minimum Degradation level for inter-annual floods

Step 8h. Evaluate reduction scenarios below Minimum Degradation for inter-annual floods

The flood assessment process required an understanding of the effects of each intra- and inter-annual flood level on geomorphological and sedimentary processes and channel hydraulics as these processes determine the physical changes that in turn govern the distribution, quantity and quality of habitat for fish, major physical bottlenecks for migratory species (e.g. waterfalls), and opportunities for spawning and foraging (see Table V). Changes in sedimentary processes can affect not only the quantity of fish habitat but also its quality, for example, accumulations of fine sediment in coarser substrate types may degrade fish spawning habitat or smother fish eggs and/or invertebrate prey. In addition, the importance of the volume and timing of floods as cues for fish spawning migration, provision of access to lateral foraging areas, and other structural and functional roles of high discharge events were considered (Table V). A marked change in the seasonal distribution (timing) of flood events may be particularly critical if flows of a particular magnitude and timing provide cues for fish migration and spawning (as demonstrated by King *et al.*, 1998). In contrast, the release of high flows from a reservoir during a normally low flow period, when some fish species are spawning, may wash away or strand incubation and larval habitat components (e.g. aquatic plants, fine substrate particles), and any associated eggs and larval fishes, with significant implications for recruitment (e.g. Pusey *et al.*, 2001a,b).

Geomorphological and sedimentary processes affected by each intra- and inter-annual flood and predictions of the attendant physical changes likely at each site were provided for each flow scenario (see Metsi Consultants, 2000a). These descriptions of physical changes were used to evaluate the ecological consequences of loss of floods. Each flood was evaluated separately, based on the predictions made by the sedimentologist and geomorphologist and the biophysical data summarized in Tables I–III.

Peak discharges of Class I intra-annual floods at site 2 ranged from 16 to 48 m³ s⁻¹ (Table II). These small floods increased channel surface area and habitat availability, and would mobilize sand and finer sediments, allowing them to be transported through the site (Metsi Consultants, 2000a). Reducing the number of such floods from six to three per annum was predicted to affect particle movement and therefore sedimentation rates, timing and frequency, as well as reducing the area of habitat available for fish. Table XII summarizes the ecological consequences of reducing the number of Class I intra-annual floods at site 2 from six to three (the Design Limitation scenario).

Inter-annual floods perform the following functions at site 2: 1 in 2 year floods initiate motion of dominant cobbles in riffles/glides and on bar surfaces, flush sediments from interstitial spaces and inundate upper bench surfaces; 1 in 5 year floods provide bankfull discharge and maintain the size of the active river channel; 1 in 10 year floods inundate upper floodplain terraces, whereas floods greater than or equal to the 1 in 20 year flood inundate the macrochannel or valley trough, and determine the size of the macrochannel (Metsi Consultants, 2000a).

Table XII. Fish consequence summary for the Design Limitation scenario (number of Class I intra-annual floods reduced from six to three per annum)

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: 16.0–48 m ³ s ⁻¹			
Flood reduction level for scenario: from six to three Class I floods			
Ecosystem significance rating: 5*			
Generic list of ecological issues affecting fish at site:			
Issue	Species	Explanation of consequences	Rating
1, 2, 3, 4, 5, 6, 7, 9, 13	Rock catfish*	A, B, D, E, Preferred seasonal timing of floods: October–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: October–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: October–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–September Social IV	Direction: –ve Quantity/Severity: 3–4 Confidence: medium

Specialists: AA = Angela Arthington, JR = Johan Rall, MK = Mark Kennard.

Ecosystem significance rating 5*: rock catfish and largemouth yellowfish are Red Data species (see Table VII).

Issue: 4 = flushing of fish eggs and larvae (see Table V).

Species: Smy = smallmouth yellowfish, Lmy = largemouth yellowfish, Orm = Orange River mudfish.

Consequence: D = change in abundance of juvenile fish (Table VI).

Direction: –ve = decrease in abundance of most species at site as the number of Class I floods is reduced from six to three.

Preferred seasonal timing of Class I intra-annual floods: October–March (spawning season for all fish except trout). Trout spawn from May to September in Lesotho rivers.

Quantity/Severity: 3–4 = few ecological requirements met, severe change in species abundance expected (Table IX).

Table XIII. Fish consequence summary for scenarios eliminating each of the 1 in 2, 1 in 5, 1 in 10 and 1 in 20 inter-annual floods at site 2 (Katse)

Study site number: 2 Discharge range for inter-annual floods: 380–870 m ³ s ^{−1} Flood reduction level for each scenario: from 1 to 0 flood Ecosystem significance rating: 5* Generic list of ecological issues affecting fish at site:			Site name: Katse Component: Fish	Specialists: AA, JR, MK
Flood frequency	Issues	Fish species	Explanation of consequences	Rating
1:2	1–15	Rc* Smy Lmy* Orm Trout	B–G Preferred seasonal timing of flood: October–March Preferred seasonal timing of floods: May–September Social IV–V	Direction: –ve Quantity/severity: 4–5 Confidence: medium
1:5	1–15	Rc* Smy Lmy* Orm Trout	B–G Preferred seasonal timing of flood: October–March Preferred seasonal timing of floods: May–September Social IV	Direction: –ve Quantity/severity: 3–4 Confidence: medium
1:10	1–15	Rc* Smy Lmy* Orm Trout	B–G Preferred seasonal timing of flood: October–March Preferred seasonal timing of floods: May–September Social II–III	Direction: –ve Quantity/severity: 3 Confidence: medium
1:20	1–15	Rc* Smy Lmy* Orm Trout	B–G Preferred seasonal timin of floods: October–March Preferred seasonal timing of floods: May–September Social II–III	Direction: 0 Quantity/Severity: 3 Confidence: medium

Specialists: AA = Angela Arthington, JR = Johan Rall, MK = Mark Kennard.

Ecosystem significance rating 5*: rock catfish and largemouth yellowfish are Red Data species (see Table VII).

Issues: 1–15 = all high flow issues were considered (see Table V).

Species: Rc = rock catfish, Smy = smallmouth yellowfish, Lmy = largemouth yellowfish, Orm = Orange River mudfish.

Consequences: B = change in fish body condition, i.e. size and weight (see Table VI).

Direction: –ve = decrease in abundance of most species at site as inter-annual floods are lost.

Preferred seasonal timing of inter-annual floods: October–March (spawning season for all fish except trout). Trout spawn from May to September in Lesotho rivers.

Quantity/Severity: 4–5 = few ecological requirements met, severe change in species abundance expected (see Table IX).

Social: IV = fishing success severely reduced, % change 51–80 (see Table X).

Table XIII summarizes the ecological consequences of eliminating each of the 1 in 2, 1 in 5, 1 in 10 and 1 in 20 inter-annual floods at site 2. Note that the actual flow scenarios did not necessarily eliminate all of these floods (see Table II). Loss of the 1 in 2 year flood was considered to have the most severe consequences at site 2 as this flood has major implications for maintenance of habitat quantity and quality for all life stages of the fish species present. It may also provide critical spawning cues one year in every two, possibly generating a large cohort of new recruits of some fish species, and possibly of all species at this site. Accordingly, this flood was maintained in the Minimum Degradation scenario (Table II), as were 1:10 and 1:20 year floods, for purposes discussed above.

DISCUSSION

In the last five decades, over 200 different approaches have been described for advising on environmental flows and they are applied in at least 50 countries (Tharme, 2003). DRIFT is a recent innovation in the category of methods termed 'holistic' approaches (Arthington *et al.*, 1992; King *et al.*, this issue; Tharme, 2003). DRIFT is a product of studies in a semi-arid, developing region where water supply issues are pressing and there is limited understanding of river ecology and how rivers with highly unpredictable flow regimes are likely to respond to water resource developments and flow regulation. In such circumstances, scientists can give precautionary, interim advice on the flow requirements of rivers and their biota using hydrological methods, or advise on the basis of limited ecological data and information supported by general knowledge and professional experience (scientific panel methods), or decline to give advice until more detailed field studies, or long-term research and model development have been completed.

As a guide to the selection of methods best suited to particular environmental flow studies, Tharme (1996), Dunbar *et al.* (1998) and Arthington *et al.* (1998) suggested a hierarchical framework to accommodate the management contexts, objectives and factors constraining environmental flow assessments. Figure 4 presents an updated version of the three-tiered hierarchy described by Arthington *et al.* (1998), indicating some of the better-known methods applicable at each level, their relative information requirements, spatial and temporal scales, and the types of issues each level is best suited to address. The hierarchy can be entered at any level and investigations may cease at any level; however, the intention is to provide a sequence of options of increasing analytical refinement and scientific certainty, and hence, increasing levels of confidence in the advice provided to managers. Conversely, the more rapid and coarse the method, the greater the risk that incorrect advice may be given and undesirable outcomes may result from management actions.

The DRIFT methodology and its fish component lie within the second level of this hierarchy of methods. They are essentially data-management tools allowing many types and sources of information, predictive models, theoretical principles and the knowledge of a panel of scientists 'to be used to their best advantage in a structured process' (King *et al.*, this issue). The use of scientific panels and 'expert opinion' is common practice in the medical/health sciences and engineering to establish new industry-wide procedures and protocols (National Health and Medical Research Council, 1994; Jones and Hunter, 1995; Anon., 1996). These methods are especially useful in situations where medical and environmental scientists, engineers, planners and policy-makers have to make urgent decisions about the protection of human health and the management of natural resources on the basis of uncertain, complex and incomplete information (Roe and Van Eeten, 2001).

A dearth of ecological data and process models upon which to base environmental flow recommendations, and political pressure to define environmental flow requirements in a relatively short time-frame (often 6–12 months), has led to frequent use of scientific panel methods in Australia (Pusey, 1998; Cottingham *et al.*, 2002). The DRIFT framework shares many features with Australian scientific panel approaches but also offers several generic advantages discussed by King *et al.* (this issue) and elaborated below.

Cottingham *et al.* (2002) comment that scientific panel methods have been 'an excellent knowledge exchange mechanism', are rapid and inexpensive compared to empirical investigations, have the flexibility to adapt the most appropriate and up-to-date assessment methods, and can make use of information ranging from anecdotal to theoretical. Their shortcomings are judged to fall into two categories: those relating to field assessments, and 'problems with panel discussions and recommendations'.

To offset these shortcomings, Cottingham *et al.* (2002) conclude that scientific panel methods would be bolstered by the development of a flexible 'best practice' approach suitable for wide application, and including the following features: (1) clear processes for selecting panel members and protocols to guide the conduct of panels and the interactions between members; (2) guidelines for developing a 'vision statement' and explicit ecological objectives, so that any ecosystem response to environmental flow provisions can be measured against the desired outcomes in an adaptive management framework; (3) more explicit guidelines regarding the selection of field sites and the collection of new field data; (4) procedures for recording the strengths and limitations of evidence used to make environmental flow recommendations; (5) consideration of the social and economic implications of environmental flow recommendations; (6) a standard process for presentation and documentation of findings; and (7) an opportunity to make recommendations on the additional information required to support or improve decisions relating to water management and, particularly, to strengthen the scientific basis of environmental flow assessments.

Level 1: Hydrological and other precautionary environmental flow assessment methods**Management context:**

Country-wide water resource planning activities; catchment-wide reconnaissance of development options; preliminary identification of opportunities for restoration of regulated systems, and low resolution, interim assessments of environmental flows at various spatial scales. Applicable when time frame, resources, expertise, and/or knowledge of hydrology-ecology relationships are very constrained.

Examples of Methods:

- Montana Method (Tennant, 1976)
- Flow Duration Curve Analysis (Stalnaker and Arnette, 1976)
- Bulk Water Estimates (Tharme, 1996)
- Range of Hydrological Variability Approach (Richter *et al.*, 1996)

Scientific rigour and risk rating:

Low scientific rigour and high risk of error.

Level 2: Holistic scientific panel methodologies**Management context:**

Catchment or sub-catchment scale assessment of environmental flow requirements at the planning stage of new developments (e.g. new dam, increased water allocation from dam, or from unregulated rivers); assessment of opportunities for restoration of regulated or abstracted river systems. Involve moderate resolution, multi-disciplinary, expert assessments of environmental flows at various spatial scales. Applicable when time frame, resources, expertise, and/or knowledge of hydrology-ecology relationships may be constrained.

Examples of Methods:

- Scientific Panel Assessment Method (Thoms *et al.*, 1997; Cottingham *et al.*, 2001)
- Building Block Methodology (King and Louw, 1998; King *et al.*, 2000)
- Holistic Approach (Arthington *et al.*, 1992; Pettit *et al.*, 2001)
- Flow Restoration Methodology (Arthington *et al.*, 2000)
- DRIFT (King *et al.*, in press)

Scientific rigour and risk rating:

Moderate scientific rigour and moderate risk of error.

Level 3: Detailed biological response and ecological response models**Management context:**

Detailed studies of environmental flow requirements at any spatial scale based on biological and ecological response models. Required for resolution of special issues (eg. fish passage requirements and/or fishway design; flows to stimulate migration and spawning, macrophyte and riparian recruitment processes, channel maintenance flows). Highly desirable as basis for all environmental flow recommendations, feasible when time frame, resources and expertise are not unduly constrained.

Examples of Models:

- SALMOD (Williamson *et al.*, 1993)
- Macrophyte biomass model (French and Chambers, 1997)
- Estuarine fish catch model (Loneragan and Bunn, 1999)
- Deterministic ecosystem models (e.g. Venice Lagoon Model, <http://f-ects.ifm.uni-hamburg.de/>)

Scientific rigour and risk rating:

High scientific rigour and low risk of error.

Figure 4. Hierarchy of methods for the assessment of environmental flows for rivers (adapted from Arthington *et al.*, 1998)

We contend that the generic DRIFT framework and the procedures applied in the biophysical and socio-economic components of the process address all of the criticisms of Cottingham *et al.* (2002) and that DRIFT compares favourably with recommendations regarding a flexible and widely applicable 'Best Practice Framework' for the conduct of scientific panel studies. In support of this assertion, we summarize below the strengths and advantages offered by DRIFT, and particularly its fish component (for ease of reference hereafter termed DRIFT-Fish), relative to other scientific panel methodologies and recommended best practice.

- (1) Guidelines for selecting scientific panel members for DRIFT projects are based upon the well-established protocols of the Building Block Methodology (King *et al.*, 2000). The roles, responsibilities and interactions of DRIFT panel members are governed by the step-by-step procedures built into the DRIFT methodology (see King *et al.*, this issue), and it is not possible for any one member to dominate the workshops or bias the outcomes of the scenario evaluations.
- (2) DRIFT and DRIFT-Fish address clear objectives by evaluating the geomorphological and ecological implications of alternative scenarios of water management and flow regulation. Some Australian scientific panel studies have commenced with very general objectives or have not evaluated alternative scenarios of water resource development, and/or flow restoration (e.g. Thoms *et al.*, 1996; Cottingham *et al.*, 2002). DRIFT, the Flow Restoration Methodology (Arthington *et al.*, 2000) and the Benchmarking Methodology (Brizga, 2000; Brizga *et al.*, 2002) all offer a transparent and explicit framework to consider the ecological implications of many alternative flow scenarios.
- (3) Cottingham *et al.* (2002) noted that many scientific panel assessments are based only on desk-top methods and 'best available information' (often very limited or of 'poor quality'), or involve little more than a rapid field assessment and single spatial/temporal 'snap-shot' of the river system conducted at sites 'assumed to be representative of the river system under consideration'. In contrast, the site selection procedures of DRIFT have a sound rationale documented by King *et al.* (this issue). DRIFT-Fish considers the core set of flow-related aspects of fish biology/ecology outlined in Pusey (1998) and Kennard *et al.* (2000), and listed above. It involves seasonal field studies at a series of representative river sites using fish survey techniques and habitat assessment protocols that have been well-tested in Australia and South Africa (Kennard *et al.*, 2000; Pusey *et al.*, 1998b, 2000; Rall, 1999). DRIFT-Fish assessments are based on the fish data set summarized in Table I and discussed in more detail below.
- (4) The level of confidence in DRIFT-Fish assessments is rated according to the information sources available and their scientific quality, thus providing the water manager with an explicit means to undertake his/her own assessment of the risks associated with management actions based on limited or low quality information. The rating scheme applied in DRIFT-Fish closely resembles that recommended by Downes *et al.* (this issue) and adapted by Cottingham *et al.* (2002) into 'levels of evidence that support environmental flow assessments'. In addition to confidence ratings, the application of DRIFT in Lesotho involved several phases of international peer review, as also proposed by Arthington *et al.* (1998) in their Best Practice Framework for environmental flow assessments.
- (5) DRIFT-Fish includes a process for evaluating the social consequences of each flow scenario, and thereby a means to estimate the economic costs of flow regulation in terms of changes in fish resources used by local rural communities (King *et al.*, this issue). This represents a significant advance of DRIFT over other panel methodologies, and avoids the charge that 'scientific panels have only "green" value-systems, and that they are an alternative environmental lobby' (Cottingham *et al.*, 2002). The Flow Restoration Methodology (Arthington *et al.*, 2000) includes a process for evaluating the 'cost' (in terms of water that would be unavailable to other users) of many different environmental flow scenarios generated by releasing flows from a large dam.
- (6) DRIFT-Fish produces a comprehensive literature review and data report describing the study area and its fish fauna, providing a major reference document and benchmark upon which to base the planning and design of river restoration activities and future assessments of river condition. In this respect DRIFT and its fish component closely resemble the comprehensive reporting procedures of the Building Block Methodology (Arthington and Long, 1997; Arthington and Lloyd, 1998; King *et al.*, 2000), the Flow Restoration Methodology (Arthington *et al.*, 2000) and the Benchmarking Methodology (Brizga, 2000; Brizga *et al.*, 2002; Kennard, 2000; Pusey, 2001).

- (7) Cottingham *et al.* (2002) did not recommend the incorporation of an explicit monitoring phase as part of scientific panel assessments, although alluding to the principles of adaptive environmental management (Walters, 1986) which are built into most other holistic methodologies (Arthington, 1998; Arthington *et al.*, 1998). All biotic components of DRIFT are required to provide a detailed rationale and protocol for monitoring the ecological outcomes of environmental flow allocations and water management scenarios (Metsi Consultants, 2000a,b). With regard to the DRIFT-Fish protocol, the predictions of fish responses to each environmental flow scenario have formed the basis of hypotheses for testing by monitoring and longer-term research. Studies of the responses of the endangered Maloti minnow to flow are now in progress based on the insights of the DRIFT fish project and earlier research on this species in Lesotho (J. L. Rall, personal communication, 2002).

In spite of the best intentions of their proponents, there are several risks associated with the use of scientific panel methods. The first is that frameworks and approaches like DRIFT may be used routinely and become all that is sought and used, rather than investing in securing new knowledge of river ecology to guide sound decision-making in the future (Cottingham *et al.*, 2002; King *et al.*, in press). Related to this threat is that best practice standards may be abandoned to simplify and hasten the assessment process; at least two instances of this 'watering down of standards' are on record in Australia (Cottingham *et al.*, 2002). In each case, budget cuts precluded the conduct of original field work in the river under study, the client perspective being that 'use of existing information is sufficient'. Another risk is that the employment of experienced river scientists may be deemed too expensive, or the non-availability of expertise in a particular country may weaken the application of the method, or the demands placed upon a few scientists (or the short-cuts required by clients; or failure to implement and monitor recommended environmental flows) may discourage their further involvement (scenarios forecast in Australia by Cottingham *et al.*, 2002).

The outcomes from application of DRIFT and its fish component, and indeed all scientific panel methods, are obviously only as sound as their scientific foundations and the quality/quantity of the data upon which decisions are based. DRIFT as applied to Lesotho rivers was a more intensive and comprehensive process than many documented environmental flow assessments conducted by scientific panels. DRIFT-Fish considers the core set of flow-related issues outlined above (Tables I, IV, V and VI), derived from published environmental flow studies and river research. We suggest that the biological information summarized in Table I represents the minimum data set for evaluation of these issues during a DRIFT-Fish assessment. If any component of this minimum fish data set is not available, original field work is essential in the river under study. Pusey *et al.* (1995a,b, 1998a,b, 2001a,b) describe methods for the collection of such data from stream and river sites.

It is obvious that the fish component of DRIFT can be strengthened by embedding quantitative methods and models linking the biological requirements of fish to the hydrological characteristics of rivers. Models such as PHABSIM (Bovee, 1982; Stalnaker *et al.*, 1994) could be applied in stable bed-rock channels, always remembering that even these methods require a considerable amount of 'expert judgement' to interpret model outputs and to select the most relevant and ecologically sound minimum and optimum flows (Gore *et al.*, 1992). Multivariate statistical models of the environmental factors and flow attributes influencing fish assemblage structure are proving useful in the design of environmental flow regimes for fish in Australian rivers (e.g. Kennard *et al.*, 2000; Pusey *et al.*, 2000). Research has been initiated to integrate a quantitative flood-pulse model of fisheries production in floodplain rivers into the DRIFT-Fish framework (R. Welcomme, personal communication, 2002). Other research developments are documented by King *et al.* (in press).

Although 'the development of deterministic ecosystem models may be an unrealistic objective because of the stochastic nature of the driving hydrological and ecological processes and the complexity of biological interactions' (Petts and Maddock, 1994), progress in this direction should be a fundamental goal for scientists involved in environmental flow studies. An integrated and interactive package of deterministic biophysical models would be a vision for the future of frameworks such as DRIFT and other holistic environmental flow methodologies.

CONCLUSIONS

The wide array of methods and frameworks applied around the world to assess the flow requirements of aquatic biota and recommend flows to protect or restore river ecosystems can be arranged into a three-tiered hierarchy. Each level of the hierarchy offers methods or frameworks appropriate to particular circumstances and management

objectives, spatial and temporal scales of investigation, resources available, knowledge base and expertise. DRIFT (Downstream Response to Imposed Flow Transformations) represents Level 2 in this three-tiered hierarchy of environmental flow methods, that is, a compromise between the use of hydrological methods with limited ecological foundations (Level 1), and the provision of scientific advice based on long-term research and predictive models (Level 3). DRIFT and similar frameworks can provide environmental flow recommendations of far greater scientific resolution than hydrological methods, by integrating many types of information and models relating the responses of riverine biota to flow modifications. DRIFT and its fish component compare favourably with recommended best practice for Australian scientific panel assessments of the flow requirements of river ecosystems.

The procedures of the DRIFT methodology and its fish component are transferable and applicable to many river systems, provided that the minimum data set describing distributions, abundance, habitat preferences, reproduction and diet are available for the fish of the study river. If any component of this minimum fish data set is not available in reports or publications, original field work is deemed essential.

The gravest risk associated with the use of scientific panel approaches like DRIFT is that they may be used routinely and become all that is sought and used, rather than investing in securing new knowledge of river ecology to guide sound decision-making in the future (i.e. moving from Level 2 to Level 3 of the methods hierarchy). Accordingly, we caution that DRIFT and other scientific panel methods should only be used where there is a genuine commitment to implement and monitor the recommended environmental flows, to support knowledge development, and to adapt water management strategies when better information about the river's responses to flow modification becomes available through monitoring and research.

In other words, the use of scientific panel methods such as DRIFT may often be necessary due to knowledge gaps and time constraints, but is not sufficient if our goal is to ensure the long-term protection of river ecosystems.

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