Using multicriteria analysis to develop environmental flow scenarios for rivers targeted for water resource management

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Abstract

DRIFT is an interactive, holistic approach for advising on environmental flows for rivers. The DRIFT methodology, together with multicriteria analysis (MCA), can be used to provide flow scenarios and descriptive summaries of their consequences in terms of the condition of the river ecosystem, for examination and comparison by decision-makers. The essential features of DRIFT, the output of workshops where it is applied, and the development of the DRIFT database are described. Modules within the database include DRIFTSOLVER and DRIFT CATEGORY. DRIFTSOLVER contains an integer linear programming MCA method, which generates optimally distributed flow scenarios for different total annual volumes of water. DRIFT CATEGORY facilitates evaluation of these in terms of river condition. These two modules are explained in detail and illustrated with examples.

Keywords: environmental flows; interactive holistic approach; DRIFT; multicriteria analysis; scenarios; river condition; integer linear programming.

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 (Arthington et al., 2003; King et al., 1999).

There are essentially two kinds of approaches to flow assessments: prescriptive and interactive (Brown and King, 2001). 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. 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 approach (Arthington et al. 2003) to advising on environmental flows for rivers (Fig. 1), developed from earlier prescriptive holistic methodologies (King and Louw, 1998), through several applications in southern Africa. It is described in detail in King et al. (2002). 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, social use, scenario development and compensation economics, Fig. 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., 2002).

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 (Fig. 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.

Essential features of DRIFT

DRIFT has several features that impart structure to specialist deliberations on the consequences of flow changes (King et al., 2002). 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

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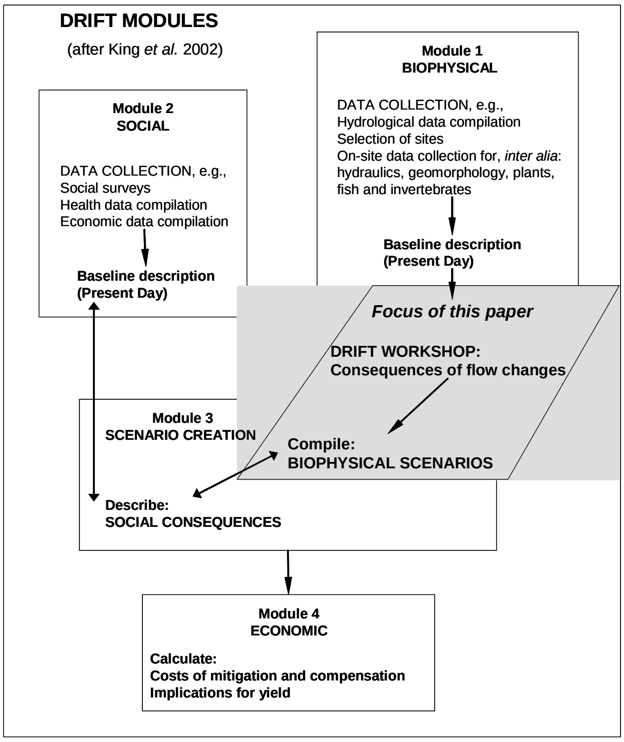

Figure 1
DRIFT modules (after King et al. 2002) and illustration of the area of focus of this paper (shaded)

into ten flow classes (Table 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, aquatic and riparian plants, aquatic invertebrates and fish (Table 1), but depending on the river under study additional components, such as mammals, birds, frogs and reptiles 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, where each specialist remains responsible for her/his own area of expertise.

When recording the consequences of each considered flow change, the specialists consider any number of subcomponents that may be relevant to their ecosystem components (Table 2, King et al., 2002). For each considered flow change at each study site, the effect on every subcomponent is described. Subcomponents 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.

The output of DRIFT work sessions is therefore a matrix of consequences, completed by the specialists, for a range of possible reductions (or additions) in the ten flow classes (Table 1), which is entered into the DRIFT database (Fig. 2), together with information on the data sources used. Each consequence is accompanied by a Severity Rating (Table 3), which indicates:

- if the subcomponent is expected to increase or decrease in abundance, magnitude or size; and
- 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 a step 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 4):

TABLE 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. (2002) for details.

Flow class	Consequences described for:	Ecosystem component
1. Dry-season low flow (range) 2. Wet-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.
3. Intra-annual floods: Class 1 4. Intra-annual floods: Class 2 5. Intra-annual floods: Class 3 6. Intra-annual floods: Class 4	4 changes in the number per annum	
7. 1:2 year flood (Class 5) 8. 1:5 year flood (Class 6) 9. 1:10 year flood (Class 7) 10. 1:20 year flood (Class 8)	Presence or absence	

TABLE 2
Ecosystem components, and possible subcomponents

Component	Subcomponents
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

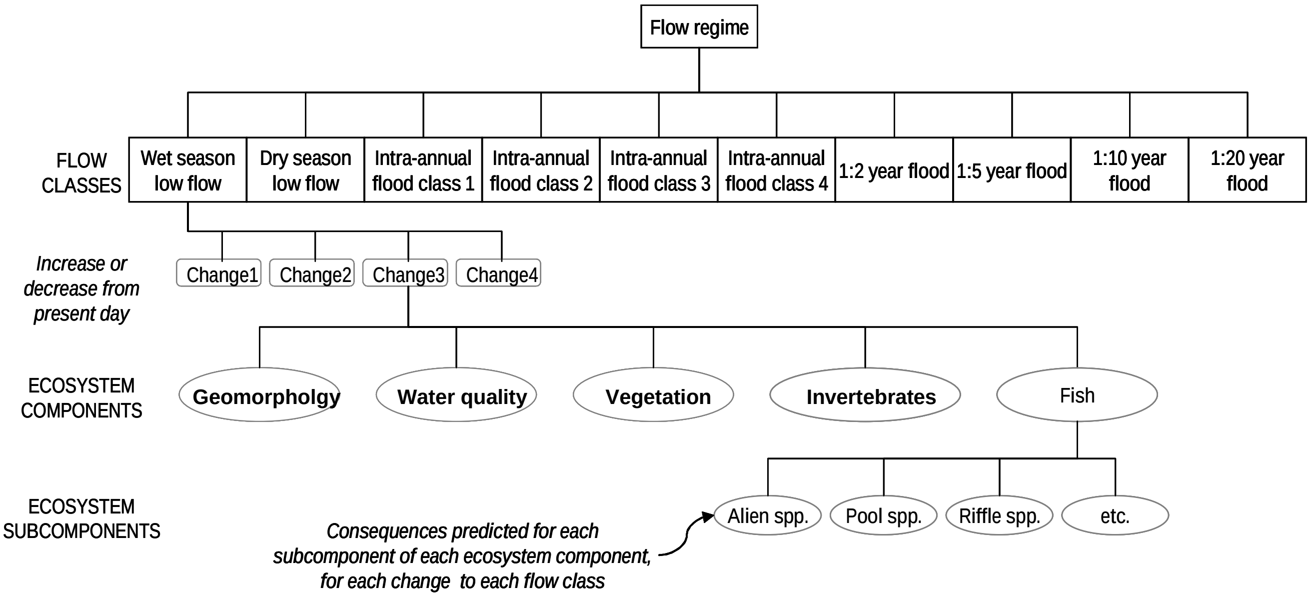

Figure 2
Framework for the database of consequences of reductions or additions in low or high flows for ecosystem subcomponents

- 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. at present 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 subcomponents (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.

TABLE 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 4
Example of a consequence entry in the database for one ecosystem subcomponent

Type of information	Information
Site	2
Flow change level	Reduction level 4 of dry-season low flows
Component	Invertebrates
Subcomponent	*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 $m^3 \times 10^6$ per annum

Use of multicriteria 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 1 000 (Brown and King, 2002), and can be as high as 30 000 (Metsi Consultants, 2000). 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.

DRIFTSOLVER

The consequence data can be combined in DRIFTSOLVER in a range of permutations to create new flow regime scenarios, together with

TABLE 5
Mathematical notation used in this paper

Notation	Designation	Range
i	Flow classes	1 to 10 (see Table)
m	Ecosystem components	1 to > 5 (see Table)
k	Ecosystem subcomponent	1 to n, for each m
j	Change level for each flow class	0*, 1, 2, 3, or 4 for each **i**
$\mathbf{x}_{\mathbf{ijk}}$	Subcomponent Integrity Rating, i.e. the effect on integrity of flow class **i** at change level **j**, on ecosystem subcomponent **k**	-5 to +5
$\mathbf{X}_{\mathbf{ijm}}$	Component Integrity Rating, i.e. the effect on integrity of flow class **i** at change level **j**, on ecosystem component **m**	-5 to +5
$\mathbf{z}_{\mathbf{ij}}$	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
$\mathbf{I}_{\mathbf{ij}}$	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.

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 to 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.

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 the different 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 subcomponents, 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 5.

Step 1

The subcomponent 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 1 to the notation in Table 5, the Fish Integrity Rating for change level 2 in wet season low flows would be $\boldsymbol{X}_{225}$, and if four species (subcomponents) were considered, the Fish Integrity Rating would be the weighted sum of their Integrity Ratings ($\boldsymbol{x}_{22k;}$ where k=1,4):

$$X_{ijm} = \sum_{k=1}^{n} w_k \, x_{ijk} \tag{1}$$

where:

w_k is the weight of ecosystem subcomponent *k*

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:

$$z_{ij} = \sum_{m=1}^{5} W_m \, X_{ijm} \tag{2}$$

where:

W_m is the weight of ecosystem component *m*

Step 3

The Flow-Level Integrity Scores ($\boldsymbol{z}_{ij}$) for all 10 flow classes (Table 1) are aggregated to give an Overall Integrity Score $\boldsymbol{Z}$ for a particular flow scenario, e.g., $\boldsymbol{Z}_{scenarioA}$:

$$Z_{scenarioA} = \sum_{i=1}^{10} \omega_i \; z_{ij} \tag{3}$$

where:

w_i is the weight of flow class i

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 $\boldsymbol{Z}$:

$$Z = \sum_{i=1}^{10} I_{ij}\omega_i z_{ij} \qquad (4)$$

where:

I_{ij} is either 0 or 1 for the particular flow change j.

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:

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

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

For TYPE 1 scenario analyses, a total volume (Q) is specified, for distribution to 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 thus an overall constraint that:

$$Q \times a > Q^* < Q \times b, \qquad (6)$$

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: $\boldsymbol{Z}$ (Eq. (4), where $\boldsymbol{Z}$ is built up from Eqs. (1), (2) and (3);

subject to the constraints of Eq. (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 6). DRIFTSOLVER was applied to find the optimal distribution of an initial specified total volume Q of 77 x 10^6 m^3 a^{-1}. The resulting scenario is presented in Table 6 (shaded levels) and comprised 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 x 10^6 m^{3}a^{-1}. In other words, the optimal arrangement of a total volume of water of Q* = 80.5 x 10^6 m^{3}a^{-1} would yield an Integrity Score ($\boldsymbol{Z}$) of -0.218, which represents a shift away from natural.

We use the five rows applying to Class 2 floods to explain Table 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:

$$\begin{aligned} \boldsymbol{z}_{41} &= (W_1 \times X_{411}) + (W_2 \times X_{421}) + (W_3 \times X_{431}) + (W_4 \times X_{441}) \\ &\quad + (W_5 \times X_{451}) \\ &= (0.2 \times 0) + (0.2 \times -0.3) + (0.2 \times 0) + (0.2 \times -0.3) \\ &\quad + (0.2 \times 0) = -0.12 \text{ (bold in Table 6).} \end{aligned}$$

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 w_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:

$$\begin{aligned} Z &= -0.02 + -0.02 + -0.01 + -0.02 + -0.06 + -0.01 + -0.06 \\ &\quad + -0.01 + -0.01 + 0 \\ &= -0.218. \end{aligned}$$

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 subcomponent w_k, ecosystem component W_m, and flow class w_i (Fig. 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 subcomponents. There are MCA techniques available that can be used to elicit appropriate weights from specialists but these were not 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

TABLE 6
Example of a flow scenario for Site 2 on the Molenaars River (natural mean annual runoff (MAR) = 160 x10^6 m^{3}a^{-1} and present day MAR = 145 x 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.

1	2	3	4	5	6	7	8	9	10	11	12	13
Flow class i	**j**	**I_{ij}**	**q_{ij}**	**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 PH	**0.2 WQ**	**0.2 Veg**	**0.2 MI**	**0.2 Fish**				
1=Wet season low flow	0	-0	47	0	0	0	0	0	0			
	1	1	31.8	0	-0.8	0	0	0	-0.15			
	2	0	24.6	-1	-1.4	-1.7	0	-1	-1	-0.15	0.16	-0.02
	3	0	12.8	-2.5	-1.9	-3	-2	-2	-2.28	(31.8)		
	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			
	1	1	8.9	0	-0.8	0	0	0	-0.15			
	2	0	6.8	-1	-1.4	-2	0	-1	-1.01	-0.15	0.16	-0.02
	3	0	4.5	-2.5	-2	-3	-2	-2	-2.29	(8.9)		
	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			
	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	-0.05	0.16	-0.01
	3	0	0.7	0	-1	-1	-0.5	-0.7	-0.63	(3.5)		
	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			
	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	**-0.12**	**0.16**	**-0.02**
	3	0	0	0	-1.1	-0.8	-2.2	-3	-1.41	**(5.4)**		
	4	0	0	0	-9	-9	-9	-9	-7.2			
5=Flood Class 3	0	0	21	0	0	0	0	0	0			
	1	0	10.4	0	-0.1	-0.2	-0.2	0	-0.09	-0.35	0.16	-0.06
	2	1	5.2	0	-0.4	-0.5	-0.8	0	-0.35	(5.2)		
	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			
	1	1	24	0	-0.13	-0.17	-0.17	0.00	-0.09	-0.09	0.16	-0.01
	2	0	12	0	-0.25	-0.67	-0.83	-1.50	-0.65	(24)		
	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	0.04	-0.06
	1	1	0	-4	0	-4	0	0	-1.6	(0)		
8=1:5 year flood	0	0	6.5	0	0	0	0	0	0	-0.8	0.01	-0.01
	1	1	0	-4	0	0	0	0	-0.8	(0)		
9=1:10 year flood	0	0	3.3	0	0	0	0	0	0	-0.8	0.01	-0.01
	1	1	0	-4	0	0	0	0	-0.8	(0)		
10=1:20 year flood	0	1	1.65	0	0	0	0	0	0	0	0.01	0
	1	0	0	-4	0	0	0	0	-0.8	(1.65)		
Q*= 80.45									$Z_{\text{scenarioA}} = \sum_{i=1}^{10} w_i z_{ij} = -0.218$			

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.

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).

DRIFT category

By rerunning DRIFTSOLVER for a Type 1 scenario with incremental increases of the per cent 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 (Fig. 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 Fig. 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 subcomponent 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 (diamond in Fig. 3).

As stated earlier, specialists' uncertainties in their predictions are expressed as a range of possible Integrity Ratings at the subcomponent level. The error bars in the DRIFT CATEGORY output (Fig. 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.

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 7; DWAF, 1999; Kleynhans, 1996) is used to illustrate this concept. In the example given in Fig. 3, the PES of the river (zero on vertical axis), as assessed by the specialists, was Category B (Brown and King, 2002). 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.

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

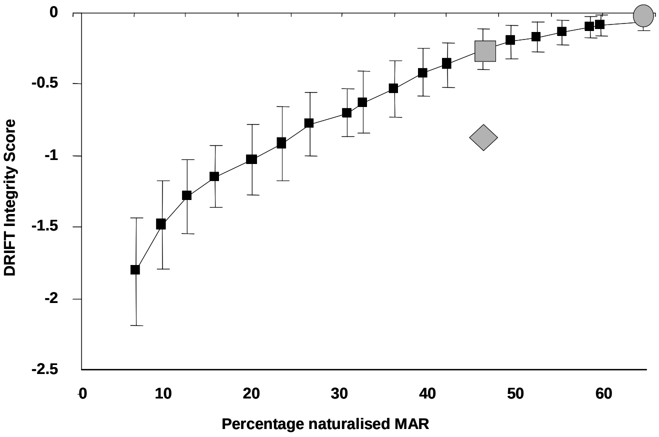

Figure 3
The basic DRIFT CATEGORY output for Site 2 on the Molenaars River, Western Cape (Brown and King 2002) showing changes in overall integrity rating for different percentages of MAR. Circle: Present Ecological State (PES); square: the (optimal) position of the scenario given in Table 6; diamond: 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. suboptimal distribution (i.e., a Type 3 scenario).

TABLE 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.

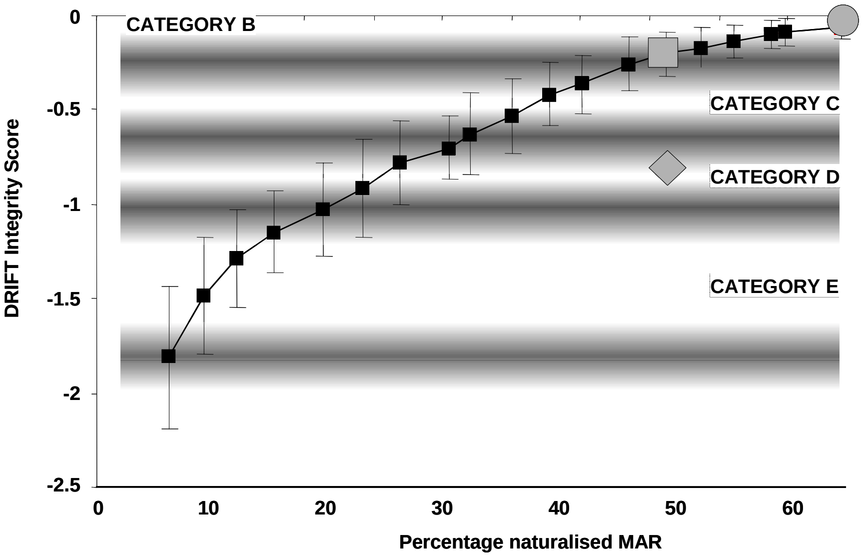

Figure 4
DRIFT CATEGORY output for Site 2 on the Molenaars River, Western Cape showing river condition categories

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 subcomponents (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 (Figs. 4 and 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 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 Fig. 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 Fig. 4).

Figure 5 gives the DRIFT CATEGORY output for a site on the upper Breede River, Western Cape. In this example, the PES of the river is Category D/E (zero on the y-axis, circle in Figure 5). 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 and Louw, 2001). An overall decline in condition, i.e., negative Overall Integrity Score, would lead to an E (or lower) category river.

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.

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 subcomponents are used as the template for

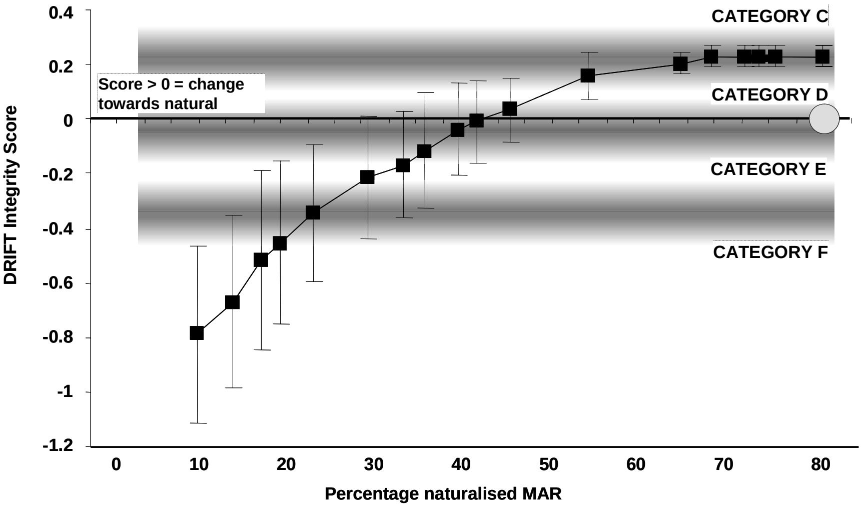

Figure 5
DRIFT CATEGORY output for a site on the middle Breede River

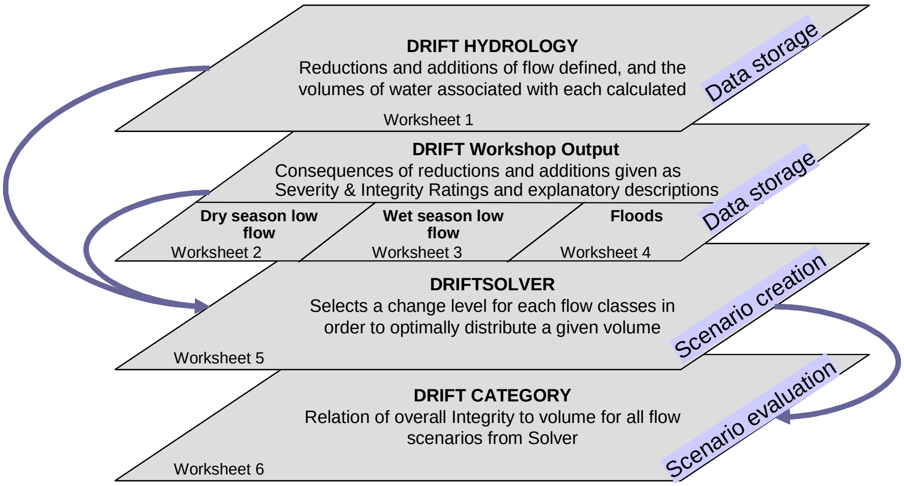

Figure 6
The Excel worksheets within the DRIFT database

predicting social impacts and their economic implications. The socio-economic procedures are addressed to some extent in King et al. (2002) and form part of the on-going development of DRIFT.

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 (Fig. 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 achieve 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.

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 need to 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. Importantly, DRIFTSOLVER and CATEGORY allow assessment of the value of making water available for river maintenance in rivers that are subjected to non-flow related impacts, which limit the condition that can be achieved or in rivers where implementing the required distribution of flows is not possible.

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

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