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DRIFT: incorporating an eco-social system network and time series approach into environmental flow assessments

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DRIFT (Downstream Response to Imposed Flow Transformation) is an interactive, ecological-social process and software package to assist with environmental flow assessments and river management decision-making. It was originally developed in the 1990s and has subsequently evolved and been applied in over 50 studies in Africa, South America, Asia and Europe. Early versions provided predicted ecological responses over time to specific flow changes, while the latest version provides responses to flow and non-flow drivers as seasonal time series. Here, an ecosystem or eco-social network is built for the river, with links between driver and responder indicators, and relationships created for each link. The network and relationships are developed and entered into the software by specialists based on available data and their knowledge. A range of scenarios is explored through the predicted indicator time series, discipline and site level ecological integrity, and social well-being. While DRIFT models vary in complexity, they are all based on relatively simple fundamental principles and arithmetic. Sequential averaging and summation through the system network is used to calculate an indicator's response to different drivers for successive seasons over time, while the discipline and site level summaries are found using weighted summation of indicator results and individual discipline results, respectively. Information from different specialist areas is therefore processed in the same way, thereby enabling coherent integration across disciplines.

Keywords: ecosystems; hydropower; linked indicators; response curves; river condition; scenarios; socio-ecological systems; time series

Introduction

South Africa has a long and proud history as a pioneer in the science of Environmental Flow (EFlows) Assessments (EFAs). Embracing modern trends of managing the health of ecosystems rather than the preservation of single species, and acknowledging the strong links between rivers and people in this developing region, the country's EFA methods have been holistic in approach from their beginnings in the 1980s. From the early prescriptive BBM (Building Block Methodology; King and Louw 1998) to DRIFT (Downstream Response to Imposed Flow Transformation) (e.g. Brown and Joubert 2003; King et al. 2014) and HFSR (Habitat Flow Stressor Response; Hughes and Louw 2010), the development of EFAs in South Africa in the 1990s played an important part in a growing global understanding of their role in guiding water resource development and river management. It is now widely recognised that if a river's flow regime changes, the river ecosystem will change. EFAs help us to understand, and therefore manage, the implications of water resource development for river health and for those who depend on this. EFAs facilitate informed, transparent and accountable decision-making by providing information to stakeholders. The information can also be used in decision-making processes. The information highlights potential trade-offs between protection and development for a particular river system. Trade-offs will differ from river to river depending on the ecological and social value of the river or its importance in other ways, for example, as a source of water for households, irrigation, industry or hydropower.

The paper describes the evolution of the DRIFT process and software from its earliest applications in the late 1990s to the inclusion of eco-social networks of relationships and the use of time series in DRIFT v4. DRIFT v4 was first used ca. 2010 and has evolved since, with the method having been widely applied for EFAs. Although applications have been widely reported, this is the first description of the method in the academic literature. The main phases of DRIFT development are described followed by more details regarding DRIFT v4.

The evolution of DRIFT within the broader EFA field

When EFlow science emerged in the 1970s to 1980s, hydrological models generally simulated average monthly flow volumes as this was felt to be adequate for planning and managing bulk water supply. However, this was insufficiently detailed for analysing the ecological and social implications of these water resource developments.

Riverine species and the people living alongside rivers tend to react to the day-to-day, or even hourly, flow conditions they experience, not monthly averages. The need for finer resolution hydrological data provided a stimulus to local hydrologists to invest in the simulation of daily flow data (King et al. 2014).

The collaborative analyses of these data by hydrologists and ecologists greatly enhanced our understanding of how flow regimes can change and how ecosystems can be affected. The resultant datasets were initially summarised in traditional hydrological ways, such as flow-duration curves, but these were not directly used by ecologists. New ways were developed to analyse, summarise and present hydrological information in a more ecologically relevant way, thus helping to identify 'flow indicators' that could be used in the assessment of eco-social responses.

The BBM

The first holistic EFlows method in South Africa was the BBM, which recognised 'baseflows', 'freshes' (or freshets) and 'floods' (King and O'Keeffe 1989; King and Louw 1998) (Figure 1), which were each associated with different aspects of the functioning of the river ecosystem. Baseflows defined the basic seasonality of the river — whether it was perennial, ephemeral or episodic, for instance, and thus the suite of species that could survive in and beside it. The terms 'baseflow' and 'low flows' were sometimes used interchangeably and sometimes as distinct terms, but both referred to lower, non-flood flows in the river. Freshes (small surges of higher flow) were seen as, for example, triggers for fish spawning and the maintenance of water quality, while floods (larger events) maintained the channel width and shape, and inundated banks and floodplains.

The BBM helped to launch new ways of understanding and summarising river flows, and of thinking about flow management (King and Brown 2010). It also influenced the inclusion of the Ecological Reserve in South Africa's 1998 National Water Act (King and Pienaar 2011). The BBM thus played an important role in South Africa's water history, but had shortcomings. It was a prescriptive approach that identified, based on the context of the river of concern, a desired level of river health and then described the flows needed to maintain it, but it could not predict the consequences of not delivering those flows. This limited its applicability, as balancing the implications of flow changes and of EFlows implementation would require a scenario building, iterative process and negotiation among stakeholders to agree on future river health and water resource development (World Bank Group 2018). Learning from the BBM, DRIFT emerged in the late 1990s as a second-generation, interactive and scenario-based EFA approach (King et al. 2003).

DRIFT v1 – flashy rivers and average values

The DRIFT process was initially developed for the montane rivers of the Lesotho Highlands and the rivers of the Western Cape of South Africa, both of which are characterised by 'flashy' flow regimes (Arthington et al. 2003; King et al. 2003; King et al. 2004; King and Brown 2010). Flashy flow regimes show responses to individual or cumulative rain events, with numerous rapid rises and falls in flow, rather than the classic 'flood pulse' (Junk et al. 1989) of many other systems. DRIFT v1 recognised ten different types or classes of flow within the flashy flow regime, each of which, it was felt, played a different role in maintaining the river (Table 1). The 10 types were distinguished mainly based on discharge.

The DRIFT process evolved in applications (e.g. Sabet et al. 2002; King et al. 2004; Brown 2007; Beilfuss and Brown 2010), resulting in an expanded list of flow indicators to summarise flow regimes, and a standardised response-curve approach. In this, relationships were developed describing how aspects of the ecosystem (e.g. a fish species) would respond to higher or lower than usual discrete levels of a chosen flow indicator. Predicted changes in the abundance of a biological indicator were then translated in a systematic way, into measures of changes in condition (health or integrity) of that indicator, then of the grouping ecosystem component or discipline (e.g. 'Fish', 'Invertebrates', or 'Vegetation'), and ultimately of the ecosystem as a whole, all within a particular reach. These concepts are expanded in later sections. The response curves were entered into the DRIFT model and results summarised in a set of structured Excel spreadsheets. Additional software was developed, using the Delphi programming language, to calculate values of each flow indicator from daily time series of discharge, for at least 15 years, generated by external hydrological models (King et al. 2004).

Although the flow indicators were felt to be ecologically meaningful by aquatic ecologists, these were often only available as an annual time-step series; however, specialists were expected to describe a single overall response (or summarised outcome) for each ecosystem indicator, to discrete levels of a summarised flow indicator. In other words, they had to estimate the potential change in an ecosystem indicator over, say, 30 years, to a particular flow indicator level occurring for 30 years. In addition, none of the flow indicators related to the onset or duration of the flow seasons, which limited their usefulness in the evaluation of hydroelectric power (HEP) developments, where the timing and magnitude of downstream flows is important.

The shortcomings of this early version were that:

- There was a small set of flow indicators, which were only relevant for flashy systems;
- The flow changes for scenarios were described as a limited set of discrete changes in discharge and flood frequency, but not timing; and
- Specialists had to integrate the potential responses over time to provide a single response per ecosystem indicator for the period of record.

DRIFT v2 – adding flood pulse rivers and annual flow indicators

As DRIFT evolved to meet the challenges of new river systems and projects, its range of applications expanded from the flashy rivers of the Western Cape and Lesotho to the season-long flood pulses of rivers such as the Mekong (King and Brown 2010). New flow indicators were needed that captured changes in the timing and magnitude of flows.

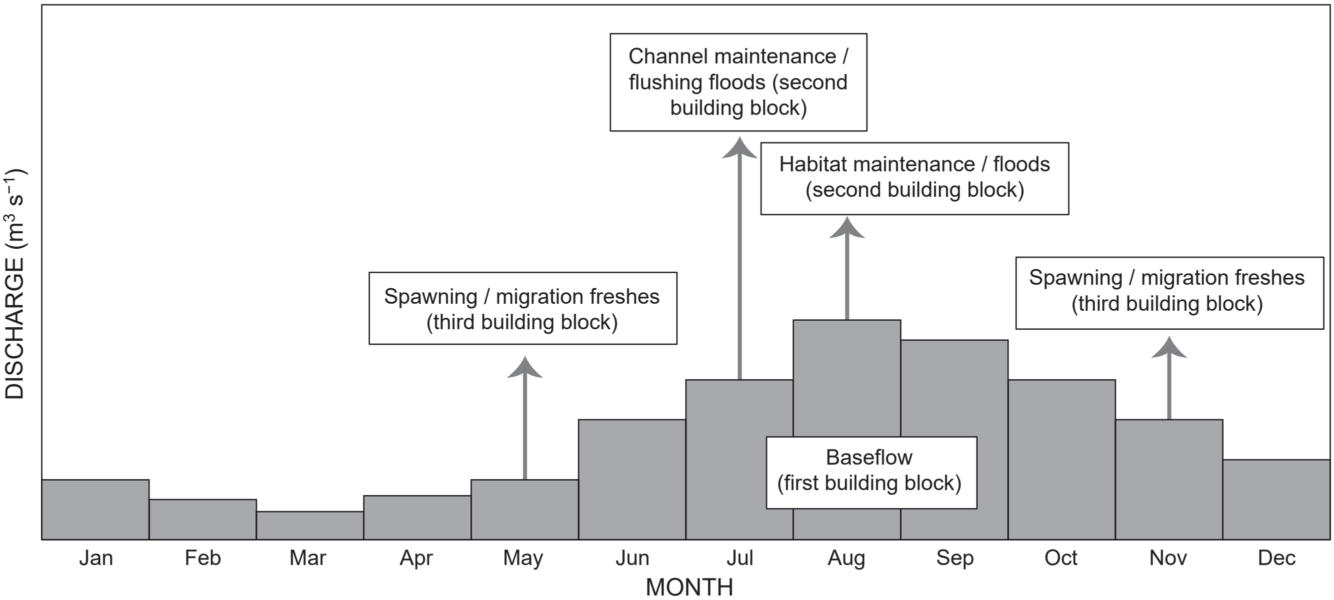


Figure 1: The concept of flows playing different roles in river maintenance and life history events, as described in the Building Block Methodology (after King and Louw 1998)

Table 1: Flow types in DRIFT v1, and their links to ecosystem functioning in Western Cape rivers, South Africa (e.g. King et al. 2003)

Class	Flow types	Ecosystem role
C1	Dry season low flows	Maintain perenniality and thus wet habitat for survival of aquatic species, trigger emergence of some insect species, maintain groundwater levels
C2	Wet season low flows	Maintain wet bank vegetation and fast-flow habitat
C3	Intra-annual floods 1	Trigger fish spawning in mid-dry season, flush out poor-quality water
C4	Intra-annual floods 2	Trigger fish spawning in early dry season, flush out poor-quality water
C5	Intra-annual floods 3	Sort sediments by size, maintain physical heterogeneity, flush riffles, scour cobbles
C6	Intra-annual floods 4	Sort sediments by size, maintain physical heterogeneity, flush tree seedlings from edge of active channel
C7	1:2 year floods	Maintain treeline on banks, scour out sediments in active channel, flood inner floodplains
C8	1:5 year floods	Maintain lower part of tree/shrub vegetation zone on banks, deposit sediments in riparian zone, flood middle of floodplains
C9	1:10 year floods	Maintain channel, reset physical habitat, maintain middle part of tree/shrub zone, flood outer floodplains
C10	1:20 year floods	Maintain channel, reset physical habitat, maintain top part of tree/shrub zone, flood extreme outer edge of floodplains

Four ecologically-relevant flow seasons were defined: dry, transition from dry to wet (T1), wet and transition from wet to dry (T2) (Adamson 2006a,b; Mekong River Commission (MRC) 2009; King and Brown 2010; King et al. 2014). From year to year, hydrological seasons start and end at different times, and their flows are different magnitudes, so methods were needed to summarise this natural variability. Rules for defining thresholds for demarcating the beginning and end of each season for each year were developed, based on principles established by Adamson (2006a,b) for the Mekong River. In summary the rules were:

- End of dry season: first up-crossing of discharge past a threshold, which is a multiple of the minimum dry season flow (D/T);
- End of transition 1: first up-crossing past a threshold which is a multiple (close to one) of the mean annual flow (T/W);
- End of flood season: first down-crossing below T/W; and
- End of transition 2: first down-crossing below D/T.

The multiples and thus the D/T and T/W thresholds are defined through trial and error for each site, based on its particular flow regime. The criteria for choosing the final thresholds are not formally defined, but consider whether the thresholds appear appropriate when plotted against the hydrograph, and that as few as possible seasons remain unidentified due to thresholds that were too high or too low. In the latter case, an unidentified season defaults for that year, and starts either a set number of days before the next season, or to a preset season date, depending on the context.

The approach proved to be a robust way to define flow seasons across a range of flood pulse rivers and wet and dry years. For example, two years' hydrographs are provided in Figure 2 for the Mekong at Xe Bang Fai [FA3

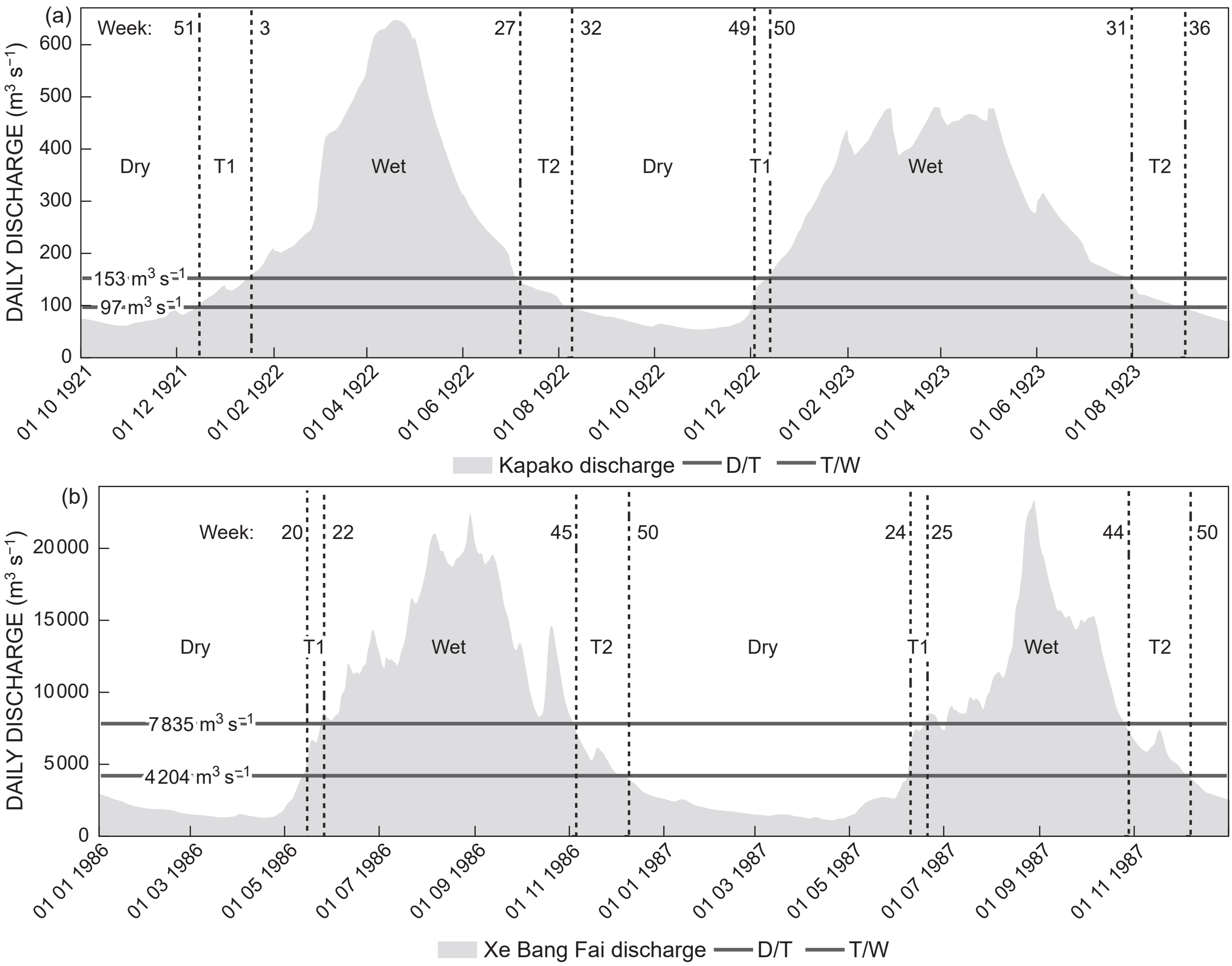


Figure 2: Hydrographs for two years, showing the four DRIFT flow seasons and the calendar weeks in which each began and ended for (a) the Okavango River at Kapako, near Rundu (1921/1922 and 1922/1923), and (b) the Mekong River at Xe Bang Fai (1986 and 1987). The horizontal lines show the (lower) D/T and (higher) T/W flow rate thresholds, and the vertical lines show the start and end of the seasons

in MRC (2017)] and for the Okavango River at Kapako [FA4 in OKACOM (2011)]. The horizontal lines are the thresholds D/T (dashed) and T/W (solid), while the vertical lines show the start and end of the dry (dashed) and the start and end of the wet (solid). The figure shows the T1 season with increasing flows starting in week 51 in the first year, at a discharge of 97 $m^3 s^{-1}$ at Kapako and in week 20, at a discharge of 4 204 $m^3 s^{-1}$ at Xe Bang Fai and ending with the onset of the wet season at 153 $m^3 s^{-1}$ (week 3) and 7 835 $m^3 s^{-1}$ (week 22), respectively.

Additional flow indicators were defined, which summarised the four seasons and the flood pulse regime. It was thereby possible to capture temporal aspects of the flow regime, such as when each season started from year to year, and how long it lasted. For example, for sites along the Okavango River, summary flow statistics were calculated for ‘Baseline’ (the relatively natural flows from 1959 to 2001) and three hypothetical scenarios of increasing water resource development (Table 2). These showed that, with the increased water use of the High Development scenario, the dry season could be up to 11 weeks longer, start up to seven weeks earlier, have minimum dry season flows drop by as much as 81%, and have a considerably reduced flood pulse, resulting in reduced flooding of the Okavango Delta.

At this stage, although the early flood pulse applications provided ecological relevant flow indicators, the *responses* of the ecological indicators were still provided as a single value covering the whole time series.

DRIFT v3 – time series indicators and results

In response to the shortcomings of DRIFT v1 and v2, DRIFT v3 was developed in 2008 and used for a project on the Okavango River basin (King and Brown 2010; King et al. 2014). DRIFT v3 marked the move to a wholly time series approach. An expanded set of flow indicators was described for each year and, unlike in previous versions, the response curves described the seasonal responses of the ecological indicators to each year’s value for the particular flow indicator. Each season’s response was

Table 2: Median predicted changes in flow indicators from the Baseline scenario through the Low, Medium and High water-use scenarios for a site (Popa) on the Okavango River (OKACOM 2011)

Flow indicator	Baseline	Low	Medium	High	Change from baseline
Dry season onset (week of hydrological year)	Aug (week 46)	Jul (week 44)	Jul (week 43)	Jun (week 39)	Progressively earlier: 2, 3 and 7 weeks earlier than baseline
Dry season minimum flow ($m^3 s^{-1}$)	114	101	93	21	Progressive decline : 89%, 81% and 19% of baseline
Dry season duration (days)	115	130	145	193	Progressively longer dry season: 2, 4 and 11 weeks longer than baseline
Wet season onset (week of hydrological year)	Jan (week 16)	Jan (week 16)	Jan (week 17)	Feb (week 18)	Delayed by 1 to 2 weeks
Wet season peak ($m^3 s^{-1}$)	620	618	611	573	Progressive very slight decline: 99.5%, 98.5 and 92.4% of baseline
Wet season volume (10^6 m^3 per year)	5269	4981	4450	3294	Progressive decline: 95%, 84% and 63% of baseline
Wet season duration (days)	150	143	129	103	Progressive shortening of flood season by 1, 3 and 7 weeks

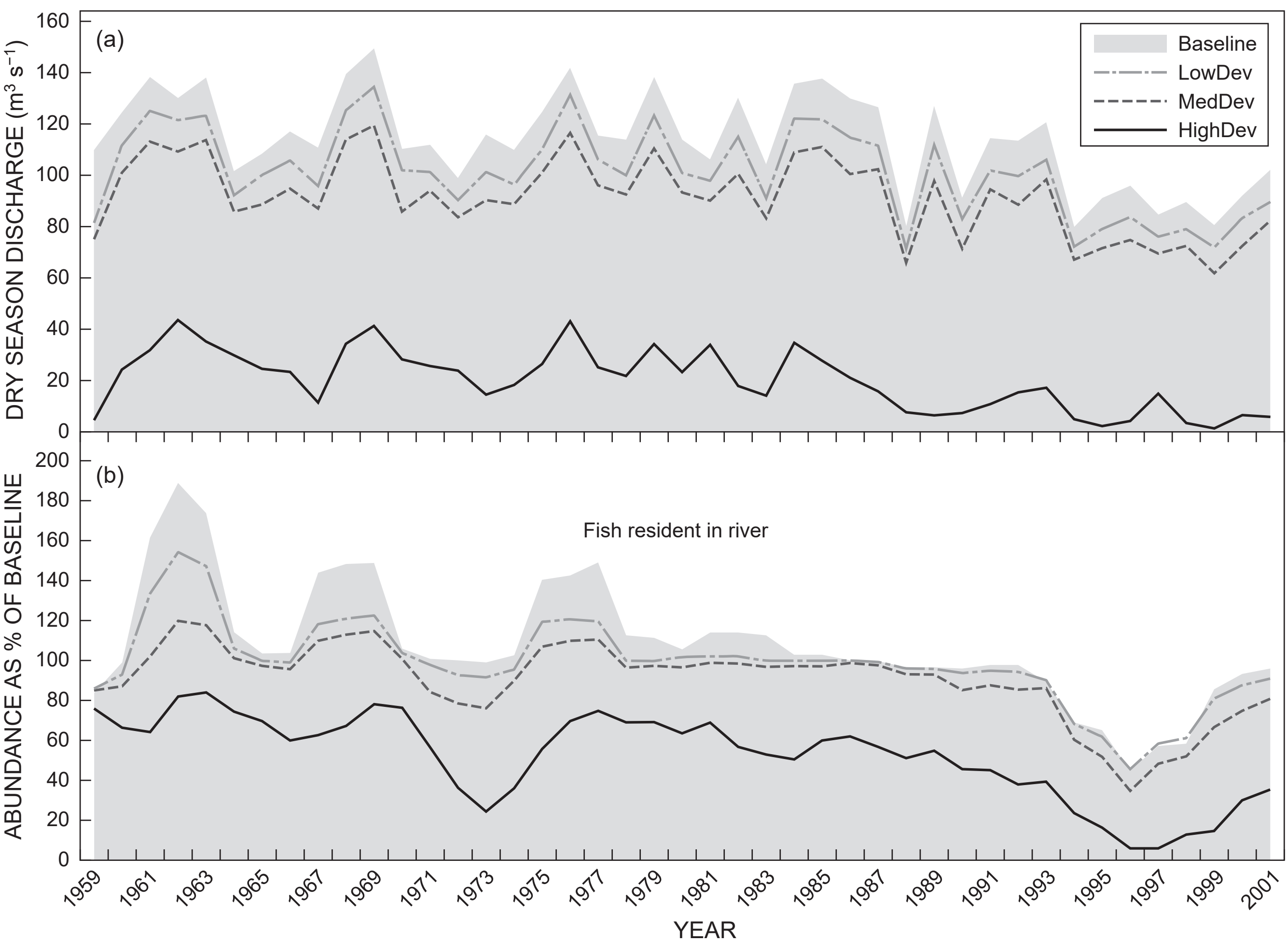


Figure 3: Time-series of (a) dry season 5-day minimum flow for four scenarios at a site on the Okavango River showing annual variation, and (b) of a fish indicator "fish resident in river" responding to this and other flow indicators

added successively to that of the previous season to produce a time series of abundance (or extent) of each ecological indicator for each scenario, as well as other summaries. This meant that the baseline scenario's predicted responses could be compared with knowledge regarding events in particular years.

For example, Figure 3a shows the time series at Site 5 for the flow indicator ‘Dry season minimum 5 day average discharge’ for the four scenarios in the 2008 Okavango study. The response, in terms of the abundance of ‘Fish resident in river’, to this and five additional flow indicators (dry season onset, dry season duration, flood season onset, flood season duration and flood type) is shown in Figure 3b.

In the Okavango project, a set of social indicators was also evaluated (e.g. fish catches, reed and grass harvests, and riverbank garden yields). The choice of indicators by the relevant specialists was based on previous work in the basin and surveys as part of the project (OKACOM 2011). Information available for use in the assessment included the types of livelihood activities, amounts of a resource harvested, techniques used, and the income derived (where relevant). Specialists from the three countries then completed the DRIFT response curves for the indicators. Although ecological indicators were linked only to flow driver indicators at this stage, social indicators were linked to both flow and biological indicators, such as fish and reed abundance. This was therefore, in effect, the first DRIFT eco-social network of indicators.

The DRIFT hydrological software of v1 was expanded to process the externally generated flow time series, provide graphs and summaries to facilitate the process of defining flow thresholds, and to calculate the flood pulse flow indicators. The flow indicator time series were then imported into a set of Excel spreadsheets for each component or discipline at each site. For each driver-responder relationship the spreadsheet was pre-populated with summary values for the flow indicators selected to be drivers, thus providing the values for the x-axes for the response curves. Where ecosystem indicators became drivers for social indicators, default x-axes were provided, from 0–250% of Baseline, with 100% of Baseline as the median value.

Later, in 2011 to 2012, DRIFT v3 was used, with adapted flow indicators, on a non-perennial river in South Africa (Seaman et al. 2016), expanding its use from flashy and flood pulse rivers to non-perennial ones.

DRIFT v3 had two main shortcomings that limited its usefulness for further applications:

- The biophysical indicators were only linked to flow indicators, whereas direct links to other habitats or food items may also have been appropriate.
- The use of Excel spreadsheets for housing the response curves and aggregating and summarising results was cumbersome and inefficient.

DRIFT v4 – building a systems network of drivers and responders

The current version of DRIFT started development around 2010 in response to the demands of new applications with a wide range of contexts and scenarios for both water resource development and resource management (Figure 4). This version uses old and new features.

Old features include:

- A time series-based approach with flow indicators, other inputs and all results available as time series.
- The ability to generate both flashy and flood pulse flow indicators from externally generated hydrological flow time series.
- The ability to link indicators to any other indicator and not only to flow, to create an eco-social systems network of cause and effect.

New features include:

- Coding of the Excel spreadsheets and previous Delphi programmes for calculation of flow indicators into the DRIFT v4 software (funded by the Water Research Commission: Brown et al. 2013), with refinements made during and between subsequent applications.
- Indicators for sub-daily flows were added to allow for responses to, for example, the hydrological effects of peaking hydropower generation.
- Provision for incorporation of additional external indicators, such as sediment transport, hydraulics, water quality, human population, and management factors, such as harvesting pressure.
- A set of modifiers was defined for each social or ecological indicator, which mediated the overall outcome resulting from the response curves, for example, through differing dependencies on the previous year’s abundance. This set of modifiers refined and expanded on the rudimentary modifiers included in DRIFT v3.

One of the first projects using the new DRIFT v4 software, was an investigation of the ecological implications of hydropower projects planned for the Neelum and Jhelum rivers in the Himalayas (Hagler-Bailly et al. 2011; King et al. 2013), followed by another for the Poonch River (Brown et al. 2019), both in Pakistan. By this stage, 29 flow indicators were defined and calculated: one annual, eight for the dry season, five for Transition 1, nine for the wet season and six for Transition 2, as well as four sub-daily indicators for each season (Table 3).

In addition to the automatically calculated flow indicators, the DRIFT v4 software can include drivers from any other source (e.g. sediment, hydraulics, water quality, human population), or indices created for the purpose (e.g. fishing types from more to less ecologically damaging, management approaches from more to less restrictive, or resulting in more to less harm). For example, as part of the Neelum-Jhelum River project, externally modelled sediment supply time series were imported into DRIFT v4. Similarly, for the Poonch River, hypothetical levels and types of fishing per scenario were imported into DRIFT v4. In later applications, such as in the lower Mekong River basin (MRC 2017), the Ravi River in Pakistan (ADB 2020) and the Okavango River basin (OKACOM 2021a,b), a large array of external indicators was added including hydraulics, water quality, human population levels, indicators for levels of natural resource use, and aspects of management, such as changes to the regulations regarding fishing gear. For example, in the lower Mekong River basin study, indicators modelled outside of and imported into DRIFT included depths, velocities, salinities, sediment concentrations, nitrogen and phosphorous levels (MRC 2017). The Ravi River restoration study also included some modelled hydraulics and water quality, while the Okavango River study included modelled hydraulics and sediment. With respect to social impacts, for the Okavango project, fishing, for example, was an important aspect of livelihoods along

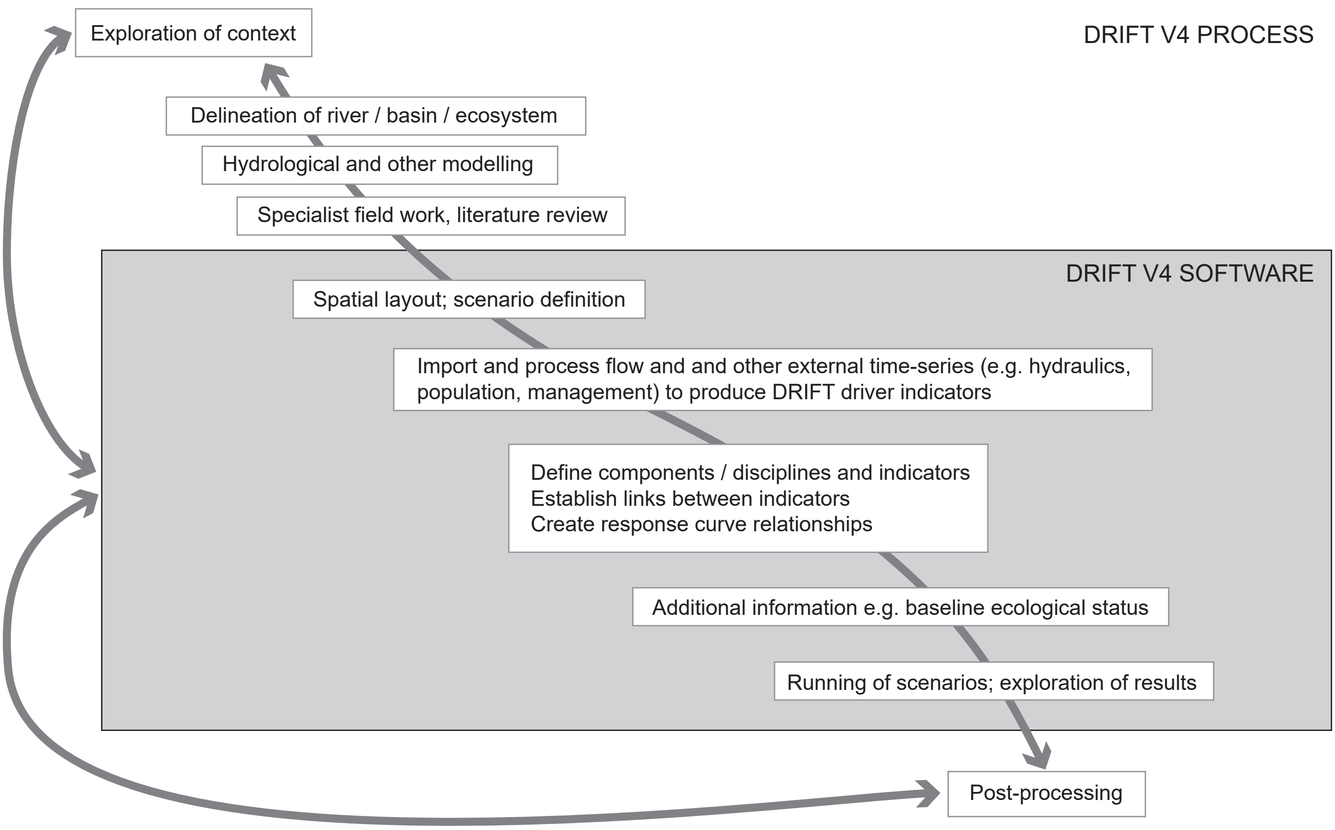


Figure 4: Outline of the stages of a DRIFT process and activities within the DRIFT V4 software. The arrows serve to indicate the iterative and often non-linear nature of the process

Table 3: The standard set of flow indicators produced by DRIFT V4, in addition to those in Table 1

Season	Indicator (Q = discharge)	Season	Indicator (Q = discharge)
Overall	Mean Annual Runoff	Wet season	Wet season onset
Dry season	Dry onset		Wet season max 5d Q
	Dry season min 5d Q		Wet season duration
	Dry duration		Flood volume
	Dry average daily volume		Wet average daily volume
	Dry season min instantaneous Q		Wet season min instantaneous Q
	Dry season max instantaneous Q		Wet season max instantaneous Q
	Dry season max rate of change		Wet season max rate of change
	Dry daily range in Q		Wet daily range in Q
T1 season	T1 average daily volume	T2 season	T2 recession slope
	T1 min instantaneous Q		T2 average daily volume
	T1 max instantaneous Q		T2 min instantaneous Q
	T1 max rate of change		T2 max instantaneous Q
	T1 daily range in Q		T2 max rate of change
			T2 daily range in Q

the river and in the delta. Different gears are more or less damaging to the environment, for example, dragnets versus hook and line. Scenarios and external indicators therefore included indices for the prevalence of different fishing gears, relative to the baseline, to represent levels of restriction and enforcement. The effect of the regulations on DRIFT indicators, such as catch (and thus social well-being) and marginal vegetation (and thus ecological integrity) was evaluated by the relevant specialists by way of response curves in DRIFT (OKACOM 2021a,b). Other social indicators included harvesting of other resources, farm yields and cultural values. Scenarios, drivers and indicators were chosen based on previous work and specialist input, and response curves provided by the relevant specialists. Feedback between management, social and ecological aspects could thus be included in the assessments. Different concerns, based on stakeholder engagements, were relevant for the restoration of the Ravi River (ADB

2020), such as recreational and cultural values, and public health. Scenario inputs and DRIFT indicators reflected these concerns.

Thus, the external indicators allow for the inclusion of a wider array of future scenarios, and a broader investigation of the influences of plans on the future status of the river system and its dependent people. This allows DRIFT v4 to be used to assess the potential impacts of combinations of water resource development scenarios, management plans and river restoration options (e.g. ADB 2020; Brown et al. 2019; MRC 2017; OKACOM 2021a,b).

DRIFT v4 response curves and calculations through the system network

Response curves

In DRIFT v4 each driver-response relationship (i.e. each line linking two indicators in Figure 5) is described by a response curve (Figure 6), which illustrates how the responding indicator would change with changes in the driving indicator if all other indicators remained unchanged at baseline. In the example in Figure 6, brown trout (*Salmo trutta* Linnaeus, 1758) had nine driving indicators of which three are shown. These included five flow indicators, two habitat indicators (clay fraction and bed sediment size), a food indicator (invertebrate abundance), and fishing pressure. The three response curves shown indicate that:

- Both early and late onsets of the dry season will negatively affect breeding and therefore abundance of the trout;
- Low dry season discharges will strongly negatively affect abundance, as there is less of a buffer against low temperatures at lower discharges, and consequently more damage from frazil and anchor ice (Maciolek and Needham 1952; Brown et al. 1994);
- Both very short and very long dry season durations would negatively affect egg survival and adult spawning, respectively.

To the right of each response curve in Figure 6 is a time series showing the result for the single driver, and below it is an explanation or motivation for the shape of the curve which the relevant specialist provides with references (if available).

In all versions of DRIFT, each response is described in terms of a percentage change relative to the chosen baseline. This usually reflects conditions at the time of the study, but any another baseline, for example natural, may be used. The specialists completing the response curves

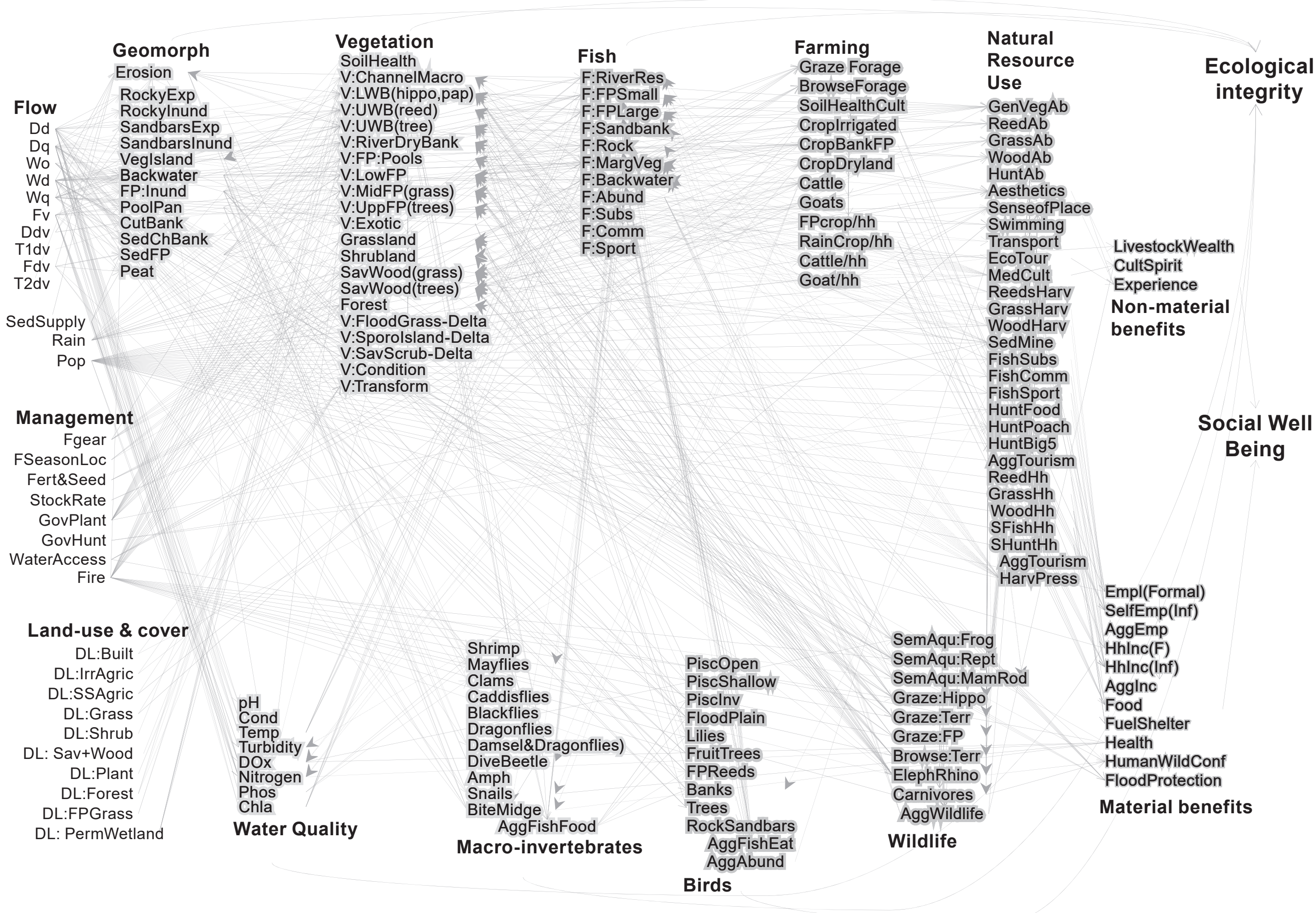


Figure 5: A representation of the web of links between driving and responding components of the Okavango socio-ecological system

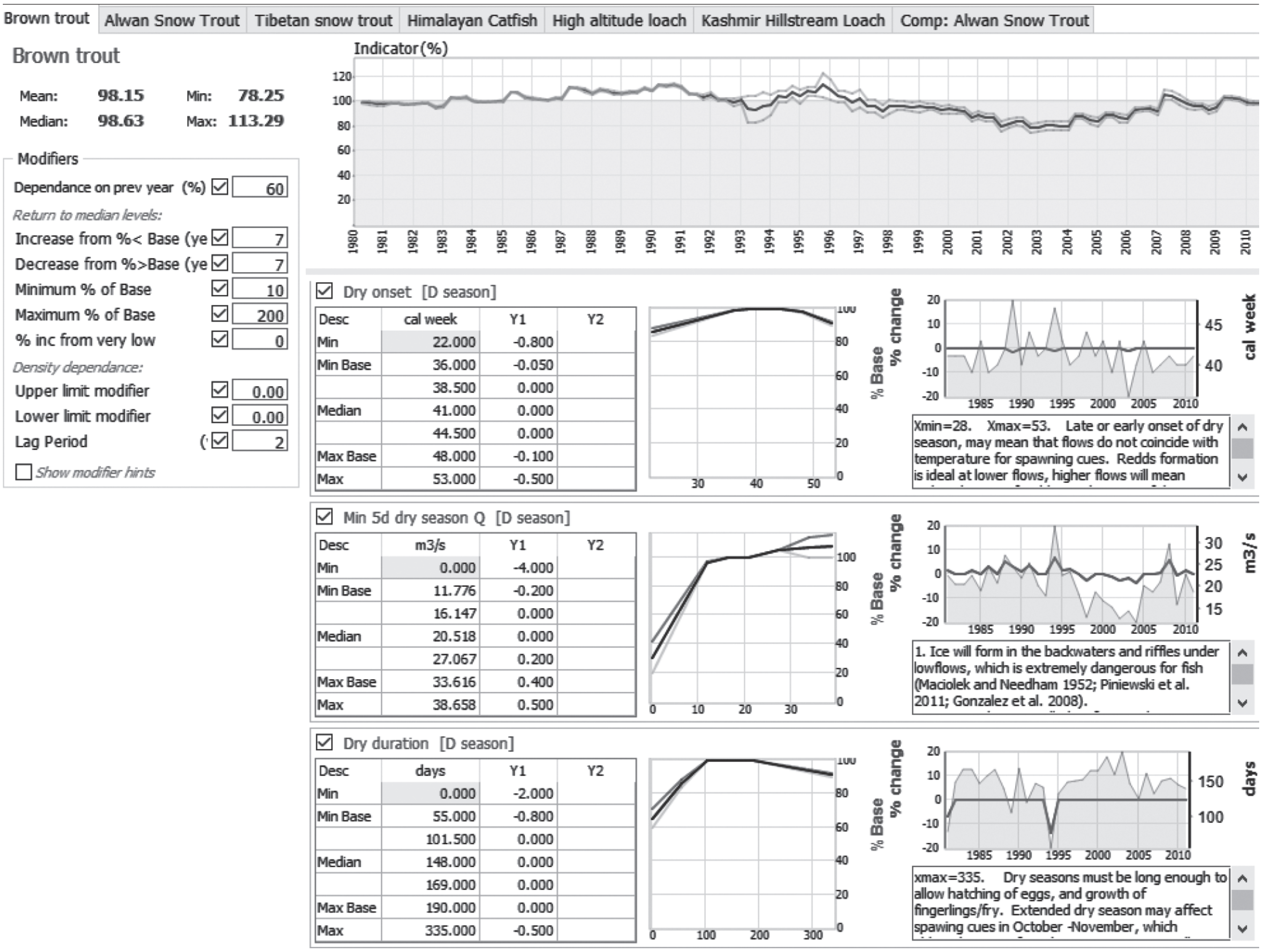


Figure 6: Response curves describing the relationship between the abundance of brown trout and three linked indicators for a site in the Indus headwaters, with motivations to the right of each response curve. The units for the x-axes are given in each of the tables on the left of the graph (e.g. “cal week” or calendar week for the first graph), while the y-axes are “%Base” or % of the baseline abundance

have to ensure that the degree of variability of the baseline time series corresponds to available data or the expected variability. For example, certain indicators, such as some fish species, may have boom-and-bust populations, while other indicators, such as riparian trees, are more stable and will show less variability. Specialists also need to ensure that, regardless of the degree of variability under the baseline scenario, the responses for the indicator collectively return a mean over time of between 98 and 102%, so that the baseline scenario averages approximately ‘100% of baseline’. Besides the internal consistency this implies, this constraint is needed so that unexpected results do not occur if the indicator in question is in turn a driver for another indicator. If, for example, the indicator averages less than 100%, a responder indicator may respond to median conditions of the driver, whereas normally median conditions would not elicit a response.

Calculating the response for a season

The response curves are compiled using severity scores, which indicate how much the indicator is expected to change with changes in the driving indicator. The scores have values from -5 to +5, which are directly translated by DRIFT into percentage changes (in abundance, extent, or concentration, etc.) (King and Brown 2006). The percentage changes range from −100% (complete local extinction) to +1 000% (increase to pest proportions). Under a particular scenario, for each response curve, DRIFT takes an incoming value for the driving indicator, which is relevant for a particular season, and takes from the curve the corresponding response, in terms of change relative to baseline, of the responding indicator (Figures 6 and 7).

In Figure 7, the median value for the dry season discharge is 20.308 $m^3 s^{-1}$. If the dry season discharge drops to around 12 $m^3 s^{-1}$ there will be a slightly negative impact on fish abundance for that season. If the dry season flow is higher than usual there will be a positive impact on abundance. The arrows in Figure 7 show the ~7% increase in the time series of brown trout abundance as a response to higher flows, and the slight decrease as a result of lower flows.

The final response of an indicator is an average of its responses from all drivers relevant to the season in

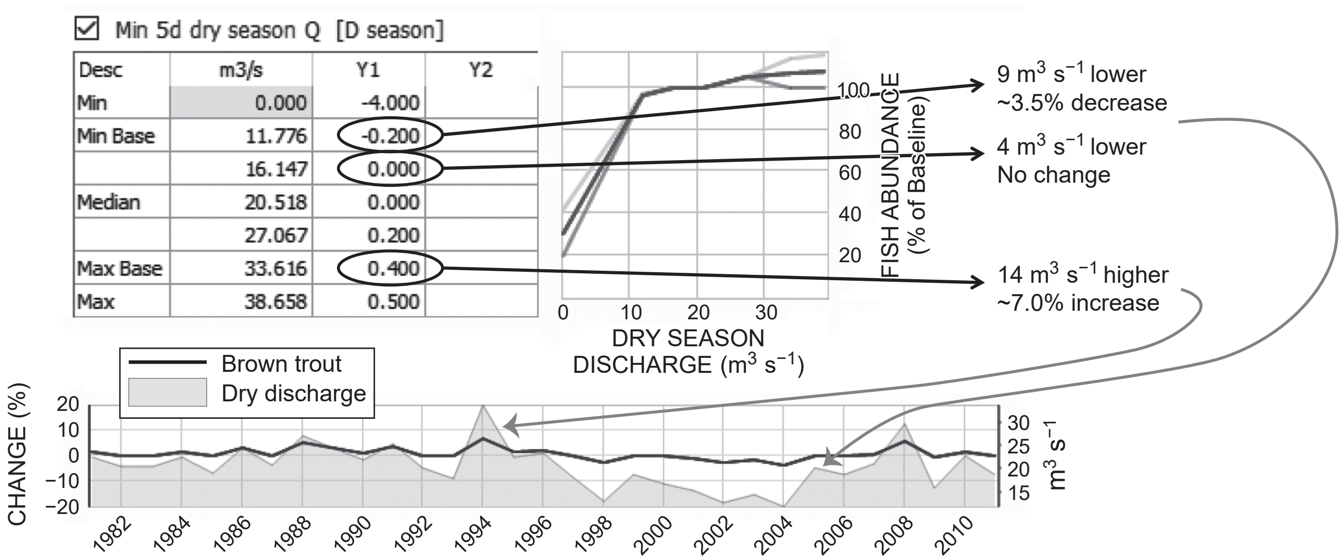


Figure 7: An example of a response curve: the relationship between dry season discharge (driving indicator) and the abundance of brown trout (responding indicator) in the Indus headwaters. The arrows show the ~7% increase in the time-series of brown trout abundance as a response to higher flows, and the decrease as a result of lower flows

question. DRIFT v4 does not currently allow for responses to be compounded (summed) within a season. For example (referring to Figure 6):

If there are three dry season drivers, and the first year of a particular scenario has the following driving values:

- Dry season onset is week 36 (5 weeks earlier than median)
- Dry season 5 day average minimum discharge is $11.8\ m^3\ s^{-1}$ ($8\ m^3\ s^{-1}$ lower than median)
- Dry season duration is 190 days (36 days longer than median), then the response for abundance of brown trout will be, respectively:
- 2% decrease
- 2% decrease
- 3.5% decrease

This will result in a predicted change in abundance of −2.5% for the dry season (the average of the three values), resulting in an overall abundance of 97.5% of baseline.

The average decrease or increase for the following season (T1) will be added to the result forthe dry season, to give the end of T1 relative abundance. For example, if the T1 indicators resulted in an average decrease of 5%, the end of T1 abundance will be 97.5% – 5% = 92.5% of baseline. Changes from the wet season will in turn be added to the T1 abundance, and then the T2 season changes will be added to the result from the wet season, thus producing the seasonal time series.

Calculations through the systems network

The calculations for a single indicator and its drivers for one season are part of a series of calculations that take place through the systems network and provide time series responses for each indicator. The calculations are not simultaneous, but follow several hierarchies, namely:

- The hierarchy of seasons: The calculations proceed from dry to T1 to wet (or flood) to T2 and back to dry;
- The hierarchy of ecosystem components or disciplines: The calculations move through a sequence specified by the user, based on an understanding of the socio-ecological system's functioning; for example, geomorphology is addressed before vegetation, and fish before birds;
- The hierarchy of indicators within an ecosystem component: (as specified by the user to follow the discipline's functioning); and
- The hierarchy of sites: Calculations proceed from upstream to downstream, and in cases of fish migration, sometimes back upstream again.

The ecosystem components (subsequent to the hydrology and other external indicators) and the indicators within them are ordered to approximate the functioning of a socio-ecological system. For example the six components below would generally be assessed in the following sequence:

- Geomorphology
- Vegetation
- Invertebrates
- Fish
- Mammalian wildlife
- Natural resource harvesting (e.g. reeds and fish).

The calculations within the model start with the first dry season and the first indicator in the first discipline (geomorphology in this example). The responses of the remaining geomorphology indicators are then calculated for the dry season, including any that react, in the dry season, to the first geomorphology indicator. Then the responses of the vegetation indicators which have dry season drivers are calculated, including their responses, if relevant, to geomorphology indicators. This is followed by the invertebrate, fish and wildlife responses to any relevant dry season drivers. This is followed by calculation of the dry season responses at the next site downstream. In the case of fish, for example, if migration is relevant to a particular fish species, the indicator at Site 2 might respond to the abundance of the same indicator at Site 1 (if they migrate downstream in the dry season). Finally, based on the abundance of reeds and fish just calculated for the dry season, if harvesting is done in the dry season, the potential harvest can be calculated.

Then, starting back at the first geomorphology indicator, the T1 response (if relevant) is calculated and added to that from the dry season, and so on.

In summary, the series of calculations to derive a time series of responses are as follows.

- An indicator's response for one season is the average of its responses to each relevant driving indicator for that season.
- A season's average response is added to the previous season's average response to get the end-of-season response.
- The last season of the year (T2) provides the end-of-year response.
- Where there is dependence on the previous year's values (i.e. in the majority of cases), the first season of the year is added to the previous end-of-year's response. Where there is no dependence on the previous year's values, the first season of the year starts with 100% of baseline as the starting value.
- The responses are in terms of percentage changes relative to baseline, and results are reported as percentages of baseline.

While the time series of individual indicator results provide a wealth of insights into the functioning of the system, summaries are also needed for decision-makers and managers. The indicator results are summarised to give an overall component-level summary of integrity, health or condition for ecological indicators, or overall percentage change from the baseline for social indicators. These may in turn be summarised at the site level to overall ecosystem integrity and overall social well-being. Whatever the chosen baseline, the integrity scores are relative to natural to indicate health rather than abundance or extent. This requires that at the outset the baseline be given a Baseline Ecological Status, from A to F relative to natural, where A is natural (e.g. Kleynhans and Louw 2008). The individual indicator's integrity is found by converting the percentage abundances back to scores (from 0 to -5), which are matched to the A to F categories. Component-level integrity is the weighted average of the individual indicators' integrity. The weights are supplied by the relevant specialist to reflect the importance of indicators to the functioning of the component. Site-level ecosystem integrity is a weighted average of the component integrities.

Modifiers

The modifiers are applied at various stages in this process. The main ones specify (a) the degree of dependence of an indicator on the previous year's abundance, and (b) how quickly an indicator will recover to its median condition given a return to median of the relevant driver indicators. The degree of dependence on the previous year will influence how the end-of-year value is added to the result for the first season in the next year. The rate at which indicators can recover after the abundance has decreased (for example as a result of a drought) or increased, influences the way a season is added to the previous season's abundance.

Presentation of results

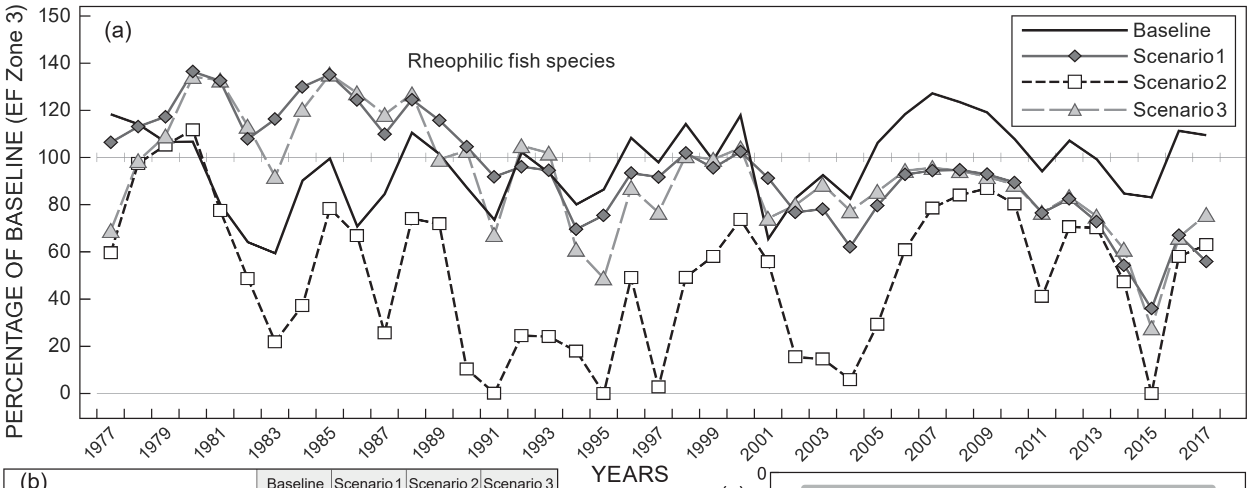
The DRIFT v4 software generates graphics and tables to assist the process and to present results. The most frequently used are those presented when calibrating the hydrological data (i.e. setting the season thresholds, Figure 2), and when completing response curves (e.g. Figure 6). The results section of DRIFT v4 includes graphs showing the time series of each indicator for all scenarios; integrity results for each component and site, and map schematics of component and site integrity. These are not felt to be of sufficient detail, quality and flexibility for reporting. Instead results are exported to a prepared Excel file where macros (Visual Basic for Applications) re-arrange, summarise and graph the results. Examples of these are given in Figure 8, rendered to greyscale for this publication.

Discussion

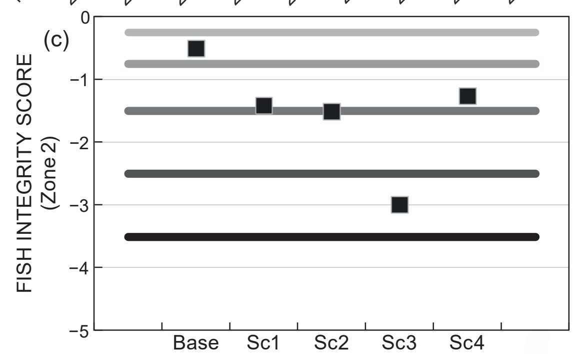
The time series-based DRIFT v4 has been widely used in southern and eastern Africa, central and south-east Asia and South America. Aspects of DRIFT development and application are provided in inter alia Arthington et al. (2003), King et al. (2003), Brown and Joubert (2003), Brown and Watson (2007), Beilfuss and Brown (2006), King and Brown (2010), King et al. (2014), MRC (2017), Brown et al. (2019), ADB (2020), OKACOM (2021a,b) and King and Brown (2021).

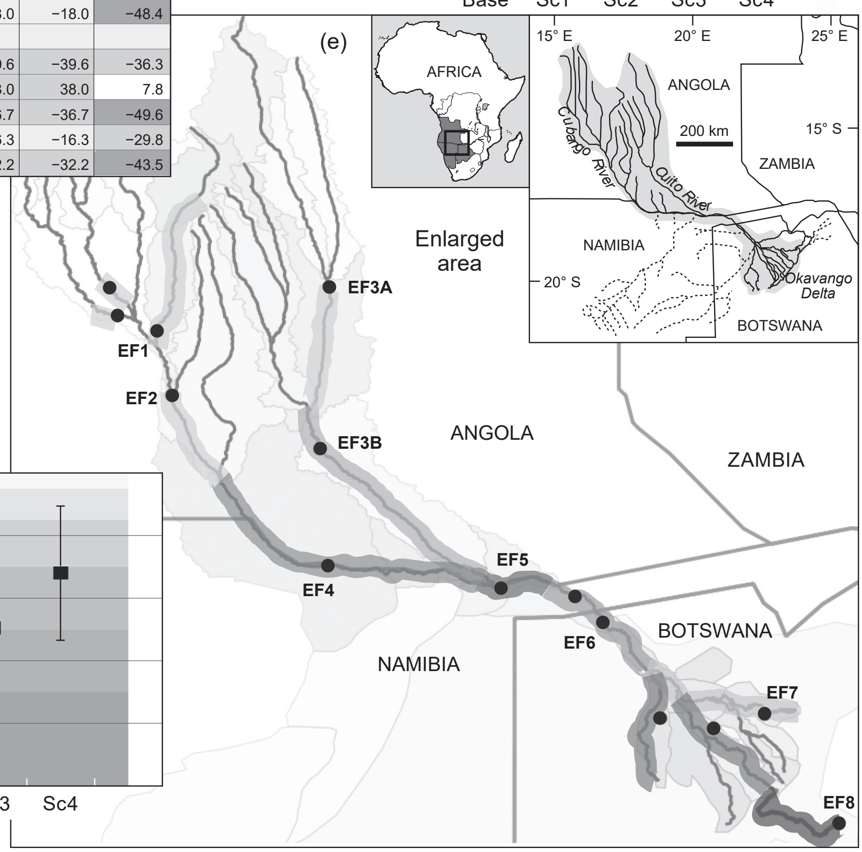
There is potentially a wide range of social and ecological impacts resulting from water resource developments, as well as a general paucity of relevant data. Thus, many kinds of information from a range of disciplines need to be drawn into EFAs (Arthington et al. 2006; King and Brown 2010; Hughes and Louw 2010; Poff et al. 2010). DRIFT has proved to be flexible and adaptable, providing a consistent, structured framework for including a range of data types and expert opinion, and helping to increase decision-makers' and other stakeholders' understanding of river functioning in a wide range of contexts.

Specialists make use of data on the river of concern or other similar rivers, local wisdom, international understanding of the functioning of river ecosystems, and expert opinion. This information is used to populate DRIFT v4 and is thus structured to allow for integration. Entries are transparent and open to amendment with increasing knowledge of the system. The use of expert inputs allows aspects previously ignored because of the lack of empirical data to be included in the analyses. With the time series approach specialists can consider responses for a particular time-step rather than needing to estimate an average response over several years as in previous methods, such as the BBM (King and Louw 1998), Bench-Marking (Brizga et al. 2002) and earlier versions of DRIFT (King et al. 2003; Brown and Joubert 2003). While specialists face an initial learning curve when first using DRIFT v4, they subsequently usually find that it prompts new insights into their discipline.



(b)	Baseline	Scenario 1	Scenario 2	Scenario 3
Geomorphology				
Erosion	0.6	16.3	16.3	15.9
Channel bank deposition	0.3	−11.2	−11.2	−10.9
Inundated sandy habitat (dry season)	−0.8	47.5	47.5	52.0
Exposed rocky habitat (dry season)	1.5	−23.7	−23.7	−29.9
Floodplain deposition	0.3	−28.9	−28.9	−48.5
Vegetation				
Rooted aquatics	−1.7	−7.2	−7.2	−16.2
Reeds	0.6	−21.5	−22.6	−25.8
Riparian trees and shrubs	0.0	−22.4	−22.4	−47.3
Wet grasses	−0.6	−22.0	−22.0	−42.5
Dry grasses	−1.1	−28.6	−28.6	−54.8
Terrestrial trees and shrubs	−1.3	−18.0	−18.0	−48.4
Fish				
Rheophilic species	0.2	−39.6	−39.6	−36.3
Limnophilic species	1.9	38.0	38.0	7.8
Floodplain dependent species	−0.4	−36.7	−36.7	−49.6
Generalist species	−0.4	−16.3	−16.3	−29.8
Cichlid species (breams)	−1.8	−32.2	−32.2	−43.5





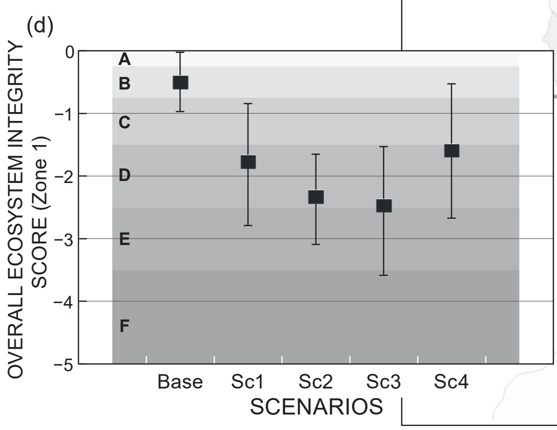


Figure 8: Examples of DRIFT v4 outputs for the Okavango Delta from Excel post-processing for DRIFT: (a) time-series for five scenarios for a fish indicator, (b) summary changes in abundance for all indicators at a site or reach, (c) integrity of the fish discipline, (d) site integrity, and (e) a GIS map of reach integrity

Of the 150 or so dams planned or under construction in Africa, at least 80% have the generation of hydroelectricity (HEP) as their main purpose (International Rivers 2015). While existing and planned HEP dams may be non-consumptive in terms of annual runoff of the rivers on which they are located, their impacts on the temporal distribution of these flows on several time scales can be enormous (Renöfält et al. 2010). Investigations of the downstream ecological and social implications of HEP dams must address these flow changes at an appropriate level of resolution spatially, but perhaps more importantly, must consider the timing, magnitude and variability of flows. DRIFT v4 is useful in this regard as it explicitly considers changes in the timing of flows and can use sub-daily instead of daily flows so that the consequences of the within-day flow fluctuations associated with peaking hydropower can be considered.

Besides the primary flow time series, time series from other models, such as hydraulic, sediment or water quality models can be imported into DRIFT v4 and used as drivers or indicators within the model. When available, climate change information can be included via modelled impacts on hydrology. Climate change impacts on rainfall and temperature can also been included as imported time series drivers.

A DRIFT v4 assessment may, therefore, be undertaken at various levels of complexity, including or excluding different components of the eco-social system, allowing for tailoring to different contexts. Over the last several years, DRIFT v4 applications have increasingly considered the social implications of flow and other proposed management changes. Which aspects are included depends on the project context, and on stakeholder engagements. A range of drivers relating to management issues and constraints, such as fishing regulations or limits to access, and social components, such as farming, consumptive and non-consumptive natural resource use, and overall social well-being have been included. This means that feedbacks between the ecosystem and social use can be modelled, and the potential benefits of changes in management approaches explored. A DRIFT v4 decision support system set up for a basin can thus be an ongoing asset, allowing authorities to continue to explore options and update the database as new understanding emerges.

Relying on response curves from specialists, DRIFT typically fits into Level 2 of the three level framework for EFA methods of Opperman et al. (2018), which was termed the 'holistic expert panel' approach. Depending on the application, the process may also include aspects of a Level 3 'holistic research-driven' assessment through, for example, the development of hydrodynamic models for floodplains and other wetlands (e.g. Birkhead et al. 2022), or sediment models (MRC 2017). In some instances, DRIFT applications have been carried out as a Level 1 assessment (holistic desktop methods), where response curves from a previous Level 2 or 3 assessment have been extrapolated to another river, and adjusted to the local setting and hydrology. This type of application of DRIFT v4 has similarities to the South African Revised Desktop Reserve Model of Hughes et al. (2014), which has aspects of both Level 1 and Level 2, but which has flow-stress relationships rather than the flow abundance (or other) relationships of DRIFT. In terms of the general process and steps, DRIFT is also similar to the ELOHA framework which evolved over the same time and has been applied primarily in the USA (e.g. Kendy et al. 2012), although there are several differences in detail. Other systems, such as SEFA (e.g. Payne et al. 2011), an updated implementation and expansion of the Instream Flow Incremental Methodology, are more data intensive, requiring habitat preference data and more detailed hydraulic modelling. HABFLOW (e.g. O'Brien et al. 2018) uses a similar general framework, but replaces response curves (continuous relationships between drivers and responders) with estimates of the relative risk to various indicators / disciplines given particular levels of the inputs, and provides probability profiles for scenarios and their associated risk levels.

DRIFT v4 has provided a number of improvements to the early versions of DRIFT. In turn, over the years, shortcomings in the DRIFT v4 software and methods have become apparent. The shortcomings of the software related to inter alia its user-friendliness, and the presentation and flexibility of graphics and tables of results. Improvements are also needed in the way that (a) flow seasons are defined and (b) ecosystem integrity is calculated. Currently, the rules for season demarcation in the software can cause the calculations to stop if several successive seasons cannot be demarcated under the scenario in question. This may happen with scenarios with severely regulated flows or the reversal of flow seasons. In some instances a small increase above a threshold for one day causes the new season to be demarcated, but the flows subsequently drop again - a mechanism for avoiding these false season starts is needed. For the determination of ecosystem integrity, the user currently specifies, for each indicator, whether an increase in the indicator would indicate a move towards or away from natural. If an increase is deemed to move the system towards natural, under this setup even very large increases will always be considered to be positive. In many cases, however, both large increases and decreases could be considered as moving the system away from natural. It is anticipated that DRIFT v5 will be produced over the next years to make these and other improvements.

As mentioned, rapid DRIFT EFAs have been undertaken by extrapolating response curves to similar systems. To improve the consistency and reliability of this process, a library of response curves is also being developed, funded by South Africa's Water Research Commission, which will facilitate rapid EFAs in systems similar to those for which detailed DRIFT analyses are available. This approach would perhaps be comparable to the Revised Desktop Model (Hughes et al. 2014), although the latter also includes aspects, such as desktop hydraulic analyses within the software.

Long-term monitoring data can be used to calibrate the time series responses for particular indicators, and enhance confidence in the results. However, monitoring programs are relatively scarce, and where they exist, the data are sometimes unavailable, or in a spatial or temporal format that is not readily useable. Monitoring of EFlows model predictions and implementations are crucial next steps towards managing rivers for sustainability.

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