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Pro-active management: the role of environmental flows in transboundary cooperative planning for the Okavango River system

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Special Issue: *Hydrological Science for Environmental Flows*

Pro-active management: the role of environmental flows in transboundary cooperative planning for the Okavango River system

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Abstract The Okavango River system flows through Angola, Namibia and Botswana. It is in near-natural condition and supports globally iconic wetlands and wildlife. The basin's people are poor and development is inevitable: the next decade is critical. The river could become an example of responsible planning that resolutely addresses the three pillars of sustainable development. Recognizing this, the Member States completed a transboundary diagnostic analysis (TDA) in 2010 funded by the three governments and the Global Environment Facility. A central feature of the TDA was a basin-wide environmental flow assessment using the DRIFT (Downstream Response to Imposed Flow Transformation) holistic approach. This produced scenarios of increasing water resource use that spelled out the costs and benefits in terms of the health of the river ecosystem, associated social structures and local and national economies. The results were used to help create a transboundary strategic action programme, which the Member States are now beginning to act on. This article describes the DRIFT application, the findings and how these could be used to help achieve sustainable development.

Key words Okavango River; holistic environmental flows assessment; DRIFT; transboundary diagnostic analysis; strategic action programme; flow indicators

Gestion proactive : le rôle des débits environnementaux dans la planification coopérative transfrontalière du système de l'Okavango

Résumé La rivière Okavango s'écoule à travers l'Angola, la Namibie et le Botswana. Elle est dans un état pratiquement naturel et des zones humides et une faune emblématiques à l'échelle mondiale dépendent d'elle. La population du bassin est pauvre et le développement est inévitable : la prochaine décennie sera critique. La rivière pourrait devenir un exemple de planification responsable qui aborderait résolument les trois piliers du développement durable. Conscients de cela, les états membres ont effectué en 2010 une analyse diagnostique transfrontalière (ADT), financée par les trois gouvernements et par le Fonds pour l'environnement mondial. Un élément central de l'ADT était l'évaluation des débits environnementaux du bassin au moyen de l'approche holistique DRIFT (Downstream Response to Imposed Flow Transformation). Des scénarios de l'utilisation croissante des ressources en eau ont été produits, en leur associant les coûts et les avantages pour la santé de l'écosystème de la rivière, les structures sociales associées et les économies locales et nationales. Les résultats ont été utilisés pour contribuer à l'élaboration d'un programme d'action stratégique transfrontalière, que les états membres commencent maintenant à mettre en œuvre. Le présent article décrit l'application de DRIFT, ses résultats et la façon dont ceux-ci pourraient être utilisés pour contribuer à un développement durable.

Mots clefs Okavango ; évaluation holistique des débits environnementaux ; DRIFT ; analyse diagnostique transfrontalière ; programme d'action stratégique ; indicateurs de débits

INTRODUCTION

In southern Africa, environmental flows (EFlows) are regarded as the pattern of flows (timing, magnitude, frequency, duration, variability), both intra-annually and inter-annually, that is identified at the end of a process of discussion and negotiation on a river basin's future. EFlows are the flow regime agreed for river maintenance and represent the optimal trade-off between conservation and development of that river at that time as agreed by its government(s) and other stakeholders. EFlows can be set for any part of a riverine system, including its floodplains and estuary, and an equivalent ecological water allocation can be set for other kinds of inland water bodies including lakes and groundwater systems.

In 2008, the Permanent Okavango River Basin Water Commission (OKACOM) initiated the Environmental Protection and Sustainable Management of the Okavango River Basin (EPSMO) Project funded by the Global Environment Facility (GEF) and the basin governments, supported by the United Nations Development Programme (UNDP), and administered by the Food and Agricultural Organization (FAO). This produced a transboundary diagnostic analysis (TDA), a major part of which was an EFlows assessment of the Okavango River system. The TDA deviated from traditional ones that assess existing development-related problems and recommend solutions. Rather, because the river is still close to pristine, OKACOM embarked on a unique TDA that looked forward to predict the positive and negative implications of possible water resource developments and then address these pro-actively through a strategic action programme (SAP) for the basin. This article describes the approach used for the EFlows assessment, the basin-wide team employed, the findings and their implications for planning and management of this basin, offering a process that can help guide truly sustainable development.

The Okavango River system is one of the world's great natural treasures. Rising in Angola, it flows south and then east between Angola and Namibia and terminates in Botswana. Its waters never reach the sea and instead spread across the flat Kalahari sands in Botswana to form a wetland of global importance that is one of the largest Ramsar sites in the world—the Okavango Delta.

Virtually the whole river system is in a near-pristine condition: as the TDA commenced, the upper basin was still largely undeveloped and sparsely populated, while the lower basin had created a significant ecotourism industry centred on the Delta in Botswana and the Namibian river reach immediately upstream. In general, the predominantly rural communities of the basin are poorer, less healthy and less well educated than others in their countries, and the National Action Plans of the three countries make it clear that development of the river system is inevitable (OKACOM 2011, and see Section 3). Much of this is likely to be in Angola, where the need is arguably greatest and the topography most amenable to hydropower and other dams, and in arid Namibia. As virtually all of the water that flows into the Delta originates in Angola, the potential for transboundary impacts as development proceeds is high.

The three countries have a rare opportunity to practice truly sustainable development of a near-pristine system, that is, to delineate a development pathway that addresses their national objectives without compromising the Okavango's global and local value. Reflecting this, the basin-wide EFlows assessment was designed to provide scenarios of the costs and benefits of a sequence of development stages. This would help the countries develop a transboundary perspective of the river ecosystem and its linked social structures and identify the trade-off point where the costs of basin development in terms of river degradation become unacceptable. The trade-off point, in turn, would indicate where and to what extent development was possible in the basin without crossing that line into unacceptable repercussions.

THE OKAVANGO BASIN

The basin covers 700 000 km^2 and has four main river-relevant geological features: the granite, quartzite and gneiss rocks of the Angolan highlands in the northeast; the vast expanse of Kalahari sands in the central basin; the Panhandle in Botswana, formed by two parallel geological faults, where the river gradually transforms into swamp; and the Kunyere and Thamalakane faults in the southeast that lie across the direction of flow and define the downstream edge of the delta (Mendelsohn and El Obeid 2004). Beyond these fault lines, intermittent outflow from the Delta at Maun along the Thamalakane and Boteti rivers feeds some ephemeral water bodies in the Kalahari Desert, including Lake Ngami and the Makgadikgadi Pans.

Although basin altitudes range from 1800 m a.s.l. at the rim in Angola to 940 m a.s.l. at the Delta, the middle basin is remarkably flat owing to the deposition of sediments over the last 65 million years. The river system, with a straight-line distance of about 1900 km, is thus actually much longer because of its meandering path, and the river network as a whole is many thousands of kilometres long. The Kalahari sands covering much of the basin are not suitable for crops because of their low nutrient levels and poor water retention. The river water is clean with low levels of minerals, nutrients and silt.

Annual rainfall decreases from north to south, with the Angolan headwaters receiving up to 1300 mm and the Delta about 450 mm. Precipitation is concentrated in the summer months, October–April, and is highly variable from daily to decadal time scales. Potential evaporation exceeds rainfall across most of the basin, resulting in its semi-arid status. The Okavango is a flood-pulse river, with a predictable prolonged flood season in the upstream basin that lasts from about December to June, alternating with a dry season with little or no rain. The flood peak arrives at the upstream end of the Delta in April and moves slowly across the Delta, taking 3–4 months to travel to Maun at its downstream end. The annual flooding of the lower reaches is thus out of synchronization with local rainfall.

The two main headwater rivers, the Cubango and the Cuito, collect water from the principal source areas: 120 000 km^2 of sub-humid and semi-arid woodland and savannah in Angola (Fig. 1). While the Cubango, to the west, is largely characterized by incised valleys, rapids, waterfalls, valley marshlands and a flashy hydrograph, the Cuito, to the east, has shallow valleys, large floodplains and a much smoother hydrograph (Mendelsohn and El Obeid 2004) (Fig. 2). Downstream of their confluence the river, now called the Okavango, is characterized by extremely shallow valleys, broad meandering channels, excised ox-bow lakes and vast, intact grassy floodplains bordered by woody plants. The Okavango flows into the Panhandle, seeping into dense bordering beds of papyrus, and on to the permanent swamps and surrounding seasonal swamps of the Delta. The largest floodplains are located on the Cuito in Angola, on the Okavango along the Angola/Namibia border and in the Delta in Botswana. The upstream riverine floodplains drain back into the river as the flood recedes, sustaining the Delta in the dry season.

The basin is globally renowned for its abundance of plant and animal life, with densities highest in the Delta and to its northeast, where up to a quarter of a million large free-roaming mammals have been counted in recent years. Few other places globally offer such a concentration of large wildlife (Mendelsohn and El Obeid 2004). Numbers decline upstream because of the nutrient poor soils, human habitation and hunting/poaching, with virtually no

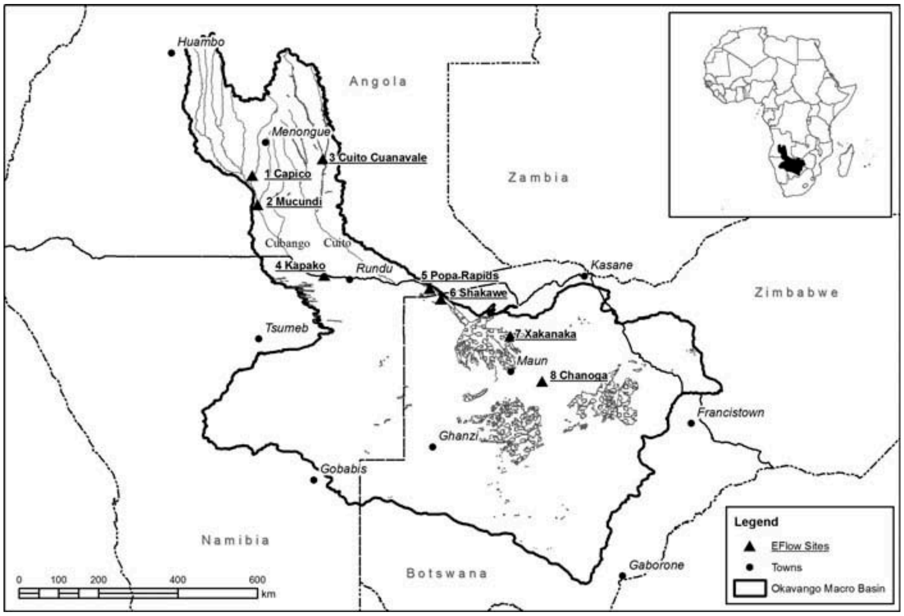

Fig. 1 The Okavango Basin, showing the two main headwater rivers, the Delta and location of the eight EFlows sites. The macro-basin was delineated according to topography and therefore encompasses runoff-producing areas in the headwater catchments, as well as large areas around the Delta that do not contribute any flow to the main river.

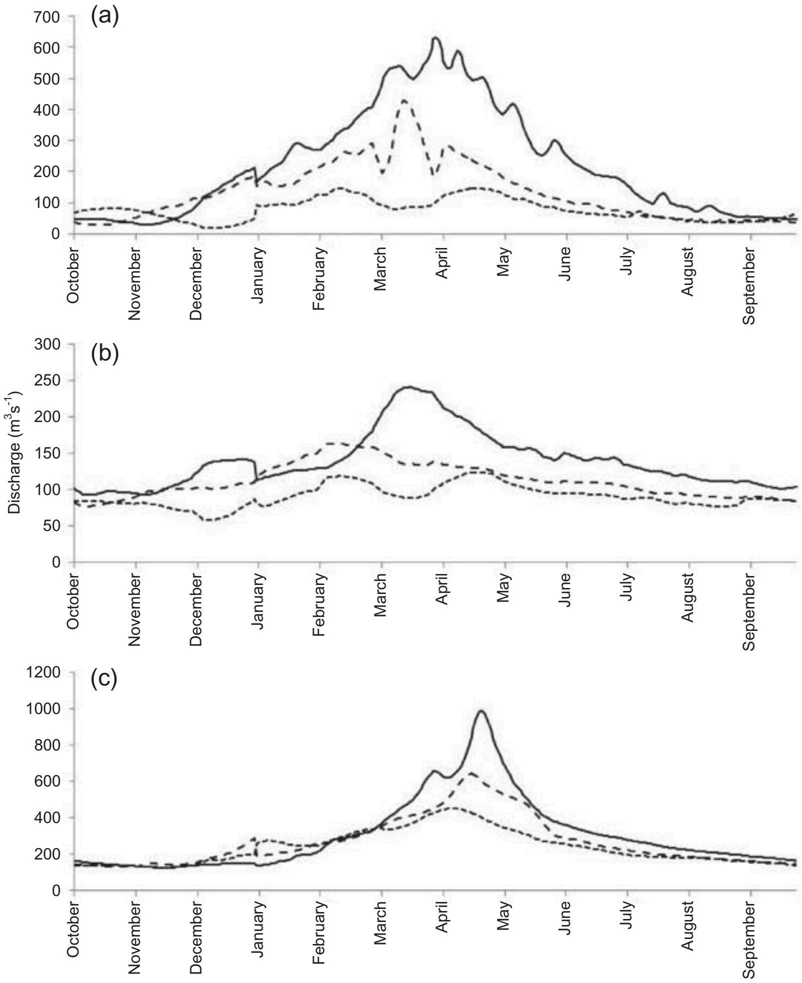

Fig. 2 Annual hydrographs for a wet (——), a dry (- - - -) and a medium (– – – –) year for the (a) Cubango and (b) Cuito headwaters, showing the different kinds of flow regimes, and (c) the resulting flows into the Delta.

large wild mammals in the Angolan part of the basin. Water birds are abundant and diverse, but fish stocks are naturally low; both are highly dependent on the annual flood.

The basin's human population is low, about 600 000 people, with about 23% urbanized in four main centres, and the majority of the remainder being small-scale farmers and fishers with strong links to the river. Livestock are common on the floodplains, and the river's plants are used for baskets, crafts, firewood and thatching grass. Its resources as a whole are most valued by local inhabitants and by global tourists, with ecotourism now the second highest earner of foreign income for Botswana.

THE DRIFT APPROACH

The EFlows assessment was done using the DRIFT holistic approach (Downstream Response to Imposed Flow Transformation; Brown and Joubert 2003, King *et al*. 2003, King and Brown 2010, Brown *et al*. 2013). DRIFT uses hydrological modelling and analyses as the starting point for the creation of scenarios that spell out the ecological, social and economic implications of possible water management plans. To achieve this for the Okavango, 12 main tasks were completed between July 2008 and October 2009 in six main streams of activities, as outlined below and in more detail in the following sections. A programme of meetings brought all team members together at key times.

First stream EPSMO adopted a capacity building, awareness-enhancing approach by appointing three full multidisciplinary teams, one from each country (Appendix), plus a process management team to guide the DRIFT application: a total of 41 specialists. Each country team contained experienced professionals in hydrology, hydraulic modelling, aquatic chemistry, sedimentology, fluvial geomorphology, aquatic and riparian vegetation, fish, aquatic invertebrates, water birds, herpetofauna, river-dependent mammals, resource economics and sociology. In addition, an economist provided an assessment of each scenario at the basin level.

The teams divided the basin into homogeneous biophysical units and social units: the biophysical units were based on hydrological, physico-chemical and biological data along the system, and the social units were based on, *inter alia*, urban population numbers, land use, the origin of household incomes and river resources used. The results were harmonized into 12 Integrated Units of Analysis (IUAs). This exercise enhanced their understanding of the whole basin and allowed data to be extrapolated from single locations to the wider IUAs that they were part of. Such an exercise characteristically takes place in most holistic EFlows approaches in some form and are called "classification of river types" in the EU Water Framework Directive (Acreman and Ferguson 2010); "river classification" in Ecological Limits Of Hydrologic Alteration (ELOHA; Poff *et al*. 2010); "catchment delineation" in South Africa (King and Pienaar 2011) and "spatial reference framework" in the Australian Benchmarking Methodology (Brizga 2006).

They next chose eight priority IUAs in areas where the likelihood of water resource development or potential conflicts over water was highest. A representative study site/area was designated in each of these IUAs, which would form the focus for modelling and data analyses (Fig. 1, Table 1).

Finally, they worked in transboundary discipline groups to identify a number of indicators: biophysical indicators were river attributes that could change with flow change and socio-economic indicators were social attributes that could change with river change. These indicators formed the focus for site visits, data collection, literature reviews and analysis that culminated in a series of specialist reports: one per discipline per country.

Second stream Scenarios are a means of exploring possible pathways into the future. They aid discussion and negotiation on what would constitute an acceptable way forward. It is critical that the scenarios are chosen by, or in consultation with, the governments and/or stakeholders or they stand the risk of being dismissed by these parties at a later stage. Three scenarios of increasing water use were chosen for the Okavango—low, medium and high water-use —plus a fourth scenario representing present-day (PD) conditions (Table 2). The low scenario included all water resource developments identified in the three countries' actual 5- to 7-year National Plans. The high scenario included every development ever considered for the river system, even though these would probably not all be possible within the basin, in order to assess how much development the river could absorb without catastrophic decline. Developments were placed in the hydrological models at likely locations in the basin, but once the DRIFT Decision Support System (DSS) was set up, the implications of other permutations and locations could easily and quickly be explored if required in the future.

Third stream A hydrological team simulated flow regimes for all sites/scenarios in parallel with the two previous work streams.

Fourth stream The DRIFT DSS software was configured and captured the biophysical and social specialists' knowledge in the form of response curves. Simulated flow regimes for each site/scenario were entered into the DSS, which used its knowledge base (the response curves) to output predictions of ecosystem change and social impact. These predictions of change were assessed and approved by the full EFlows team in a scenario meeting in June 2009.

Fifth stream The implications of climate change were added to the project later by re-running the low

Table 1 Location of the sites for the EPSMO EFlows assessment.

Site	Country	River	Location	Coordinates
1	Angola	Cuebe	Capico	15°33′05″S; 17°34′00″E
2	Angola	Cubango	Mucundi	16°13′05″S; 17°41′00″E
3	Angola	Cuito	Cuito Cuanavale	15°10′11″S; 19°10′06″E
4	Namibia	Okavango	Kapako	17°49′07″S; 19°11′44″E
5	Namibia	Okavango	Popa Rapids	18°07′02″S; 21°35′03″E
6	Botswana	Okavango	Panhandle at Shakawe	18°21′16″S; 21°50′13″E
7	Botswana	Khwai	Xakanaka in Delta	19°11′09″S; 23°24′48″E
8	Botswana	Boteti	Chanoga road bridge	20°12′51″S; 24°07′37″E

Table 2 Details of the possible developments included in the EFlows scenarios.

Scenario	Details
Present Day (PD)	2200 ha irrigation in Namibia
Low water-use (equates to national 5- to 7-year plans)	All PD developments, plus:
	3 100 ha irrigation in Namibia
	18 000 irrigation along the Cuebe River in Angola
	One storage-based and three run-of-river hydropower stations in Angola
Medium water-use (possible 10- to 15-year planning horizon)	All PD and low scenario developments, plus:
	Increased water demand for people and livestock as per projections
	8 400 ha irrigation in Namibia
	198 000 ha of irrigation in Angola (various locations)
	Phase 1 transfer of 17 10^6 m^3 $year^{-1}$ of water to the Eastern National Water Carrier in Namibia
	One storage-based and four run-of-river hydropower stations in Angola
High water-use (possible 20-year plus planning horizon)	All PD, low and medium scenario developments, plus:
	Increased water demand for people and livestock as per projections
	15 000 ha irrigation in Namibia
	33 800 ha irrigation in Angola (various locations)
	One storage-based and nine run-of-river hydropower stations in Angola
	Phase 2 transfer of 83 × 10^6 m^3 $year^{-1}$ of water to the Eastern National Water Carrier in Namibia
	Development of water abstractions from the Delta for water supply to communities on the western fringe of the Delta and urban and industrial water supply to Maun

and medium scenarios with the driest and wettest climate change predictions superimposed (results not provided in this article).

Sixth stream The findings were included in the TDA and formed part of the foundation of the basin-wide SAP.

All of the above and their outcomes are detailed in a series of 59 process and specialist reports at http://epsmo.iwlearn.org/publications/envana/final-tda-report.

THE HYDROLOGICAL MODELLING AND ANALYSES

Objectives and personnel

The two main objectives were to:

(1) develop daily streamflow sequences for each of the EFlow sites for PD conditions and for each scenario; and
(2) transform these flow sequences into ecologically-relevant flow statistics for ecological analysis.

To achieve this, a working group was formed consisting of hydrologists from the three Member States and an international water resource modeller. In five week-long workshops in 2008–2009, they prepared the hydrological data for the PD and three future scenarios for each site (Table 2). The composition of the working group was crucial; the three Member States worked together to produce hydrological data sets that were accepted by all.

Available hydrological data and models

The Delta has a well-developed hydro-climatological monitoring network, with some streamflow records dating back to the 1930s, and several hydrological models. By contrast, hydrological data for the upper river in Angola are few with many gaps. To provide the basin-wide hydrological information required by the project, a linked ensemble of models covering the data-poor upstream catchment, the relatively well studied Delta and the Delta outflows into the downstream Boteti/Thamalakane system was configured.

Upstream catchments

Catchment hydrology Estimates of naturalized (undeveloped) long-term runoff were obtained from an existing Pitman-based rainfall–runoff model (Pitman 1973) developed as part of the EU-funded Water and Ecosystem Resources for Regional Development project (WERRD; Hughes *et al.* 2006). The model was configured to provide runoff sequences at the outlets of 24 sub-catchments upstream of the Delta. A notable feature was its use of Tropical Rainfall Measuring Mission (TRMM) and Special Sensor Microwave Imager (SSM/I) satellite-based rainfall estimates to overcome the complete lack of measured point rainfall in the upstream basin after 1972 (Wilk *et al*. 2006).

Systems model The catchment hydrology was incorporated into the monthly time-step WEAP systems model to simulate the PD, low, medium and high water-use scenarios. Inputs to the model included the undeveloped runoff sequences produced by the Pitman model for the 24 sub-catchments, demands for irrigation schemes and urban abstractions, in-channel dams for irrigation water supply, inter-basin transfers, and both run-of-river and storage-based hydropower schemes (Table 2).

The Delta

HOORC Delta model A hybrid-reservoir-GIS model previously developed by the Harry Oppenheimer Okavango Research Centre (HOORC) (Wolski *et al*. 2006) was used to model inundation frequencies and extents at the Delta EFlows sites. The model operates on a monthly time step and includes a dynamic ecotope model that simulates the responses of vegetation assemblages to changes in hydrological conditions. Scenario inflows to the model are provided by the WEAP simulations of basin runoff.

DWA Delta model A MIKE-SHE/MIKE 11 hydrodynamic model previously configured by the Botswana Department of Water (DWA) and the Danish Hydraulic Institute (DHI) for the Okavango Delta Management Plan (ODMP 2008) was used to model flow velocities and depths at the Delta EFlows sites. Scenario flow sequences simulated with WEAP for Mohembo (near Site 6) were used as inflow sequences for the Delta model, after disaggregating the monthly flow sequences to a daily time step.

Delta outflows

Thamalakane/Boteti model Delta outflows simulated by the HOORC model were routed along the Thamalakane/Boteti system using a linear reservoir spreadsheet model (Mazvimavi and Motsholapheko 2008) to derive scenario flow sequences at the Boteti EFlows site. The model was incorporated into the HOORC Delta model and improved to provide estimates of wetted river length and state changes of the system.

Combining the models and disaggregation

The upstream catchment model, delta flooding model and delta outflow model were combined to produce times series of monthly flows for a 43-year hydrological period (1959–2001) for the river sites in the upstream catchment (Sites 1–6) and a 20-year hydrological period (1983–2002) for the Delta (Site 7) and the Thamalakane/Boteti system (Site 8). For each scenario, the level of water use outlined in Table 2 was imposed on the full hydrological period. The three models were run independently, in sequence from upstream to downstream, and linked by using outflows produced by upstream models as inflows to the downstream models.

The monthly time series for the upper sites were disaggregated to daily data, guided by nearby measured flows. A custom utility was developed both for the disaggregation exercise and to delineate flow seasons (dry, wet and transition) for each year of the 43-year sequence. Disaggregation was done because this provided the detail of daily flow conditions faced by the ecological and social structures of the river, which are masked by monthly average data. Simulations of daily flows may be imprecise, but the greater requirement is that they characterize the flow regime at a time step that the living system experiences and reacts to.

Interpretation of hydrological flow sequences

The daily flow and other sequences produced by the hydrological group are not, as they stand, easy to interpret ecologically. They were therefore transformed into summary statistics of a set of flow indicators chosen by the ecologists and resource economists.

Hydrological indicators for the upstream catchment (sites 1–6) The ecologists recognized two main flow seasons: the dry and flood, with transitional seasons between. The hydrological indicators of most importance were the following:

(1) Mean annual runoff (MAR) (10^6 m^3 $year^{-1}$)
(2) Dry season onset (calendar week)
(3) Dry season duration (d)
(4) Dry season minimum 5-day flow (m^3 s^{-1})
(5) Flood season onset (calendar week)
(6) Flood season 5-day peak (m^3 s^{-1})
(7) Flood season volume (10^6 m^3)
(8) Flood season duration (d)
(9) Flood season type (types 1 to 6).

The 43-year PD daily flow record was divided into the four flow seasons according to a set of rules that was calibrated for each site (e.g. Kapako, Table 3).

Table 3 Delineation rules for the flow seasons at Kapako (Site 4).

Season boundary	Calibrated rule
End of dry season	2.1 × minimum 5-day dry-season discharge
End of transition 1	First up-crossing of the mean annual discharge, which is 168 $m^3 s^{-1}$ at Site 4 (see Fig. 3)
End of flood season	Last down-crossing of mean annual discharge
End of transition 2	Average recession rate over 15 days < 1.2 $m^3 s^{-1} d^{-1}$ OR down-crossing of 2.1 × minimum 5-day dry season discharge

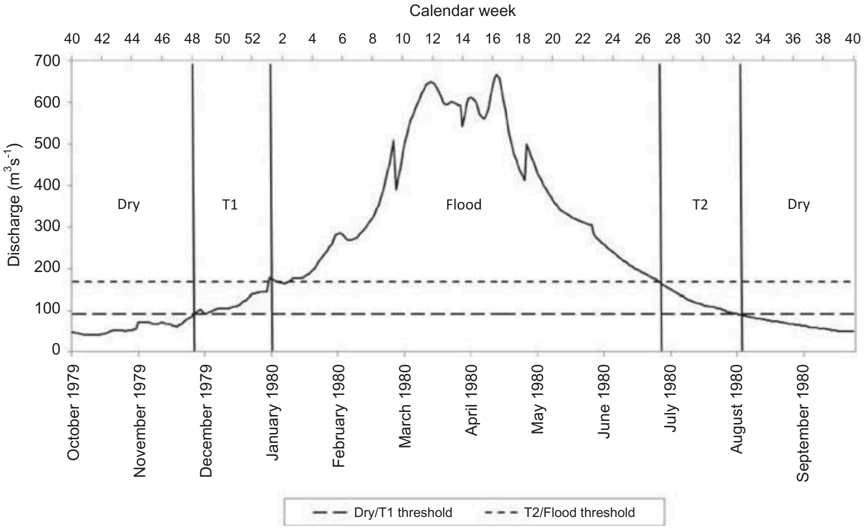

Fig. 3 Annual hydrograph and delineation of flow seasons at Site 4 for the 1979/80 hydrological year.

This produced well-defined Dry, Transition 1 (T1), Flood and Transition 2 (T2) flow seasons for each year of the modelling period (Fig. 3). The calibrated rules were then used to recognize the same flow seasons in all future scenarios. Each type of flow season started on a different day each year, reflecting natural variations of the hydrological cycle and, in the scenarios, human-induced changes such as delays in flood season onset caused by reservoir filling. The flood season type (flow indicator (9)) is a combination of flood peak and volume, which provides an indication of the nature of the flood season and thus the extent and duration of floodplain inundation (Fig. 4).

Hydrological indicators for the Delta (Site 7) Flow sequences are not particularly useful in a hydrological analysis of the Delta because water spreads slowly across the landscape, with the vegetation types and aquatic habitats driven by the extent and frequency of inundation. Additionally, the overall proportion of inundated area may be similar in years with similar flow characteristics, but the location of the inundated areas may vary. For this reason, the HOORC hybrid-reservoir-GIS model was used to generate monthly inundation patterns over the northeastern portion of the Okavango Delta, as represented by Site 7, Xakanaka. The Delta is hydrologically extremely complex, with a mosaic of different flooding and draining regimes; it is acknowledged that no single site could represent all of it, and Xakanaxa may not well represent the extensive and ecologically significant seasonally pulsed portions in the west of the Delta.

The output of the model is a series of vegetation types/habitats, which acted as the hydrological indicators for the Delta:

(a) Channels in permanent swamp (CH-ps)
(b) Lagoons in permanent swamp (L-ps)
(c) Backswamp in permanent swamp (BS-ps)
(d) Seasonal pools in seasonally flooded zone (SP-sf)
(e) Seasonal sedgeland in seasonally flooded zone (SED-sf)
(f) Seasonal grassland in seasonally flooded zone (GR-sf)
(g) Savannah: dry areas in seasonally flooded zones (S-sf).

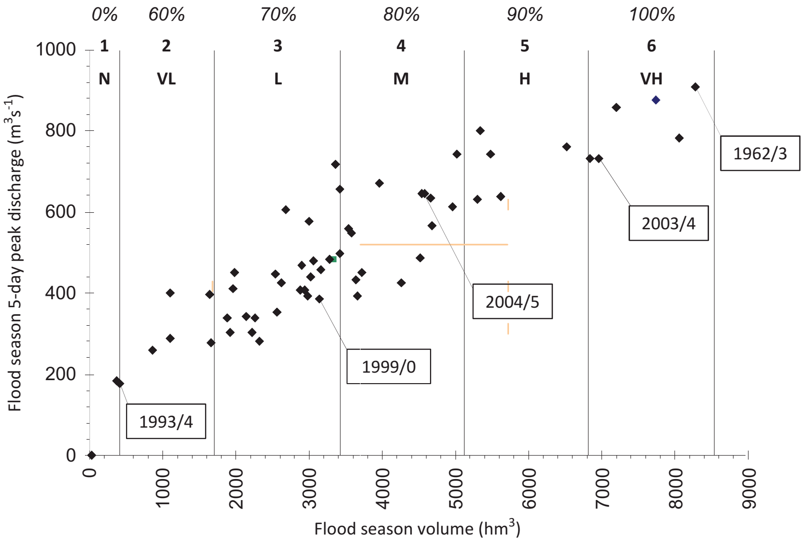

Fig. 4 Identification of six flood types from the plot of historic flood peak *vs* flood volume for Site 4. The percentages indicate the approximate degree of floodplain inundation: N: no flood; VL: very low; L: low; M: moderate; H: high; VH: very high. Some recent flood years are shown.

Hydrological indicators for the Thamalakane/ Boteti system (Site 8) The Thamalakane/Boteti River system receives outflows from the Delta and is highly susceptible to changes in the flooding regime of the Delta and the state of the groundwater aquifers in previous years. The system normally experiences dry and wet cycles of several years duration. The hydrological indicators selected were expressed as the percentage of a 200-km-long study reach on the Boteti River that would be:

(a) Wet
(b) Partially wet—isolated pools, or
(c) Dry.

Predictions of hydrological change through the scenarios

The upstream catchment There would be a progressive change in the value of all flow indicators through the sequence of scenarios. The impacts would become increasingly transboundary, with inflows to the Delta decreasing by 344, 823 and 2704 × 10^6 m^3 $year^{-1}$ through the low, medium and high scenarios, respectively, relative to the PD MAR of about 9123 × 10^6 m^3 $year^{-1}$.

Table 4 summarizes the predicted changes in hydrological indicators for Site 6 through the three scenarios. Flows at this site reflect the combined effect of all modelled water resource developments in the upstream Angolan and Namibian catchments before the water enters the Delta. Under the high scenario, MAR would decline to 70% of the PD value. The dry season would start up to 2 months earlier and be almost 3 months longer, with flows reduced to 18% of present flows. The flood season onset and peak would be only slightly affected, but the duration of flooding would be up to 2 months shorter and reduced to about two-thirds of its present volume. There would be a shift away from higher floods toward lower ones, with the data suggesting that very high floods would tend to be reduced to high ones and moderate floods to low and very low ones. This drift toward weakened floods would impact the integrity of the floodplains.

The same trends would be evident basin-wide, with the lower sites showing the greatest impact. There would not be a marked transfer of water from the flood season to the dry season, as with many developed basins, because there would be no dams with sufficient storage to affect this.

The buffering effect of the Cuito River was shown to be vitally important to the lower part of the system. Its large floodplains store significant volumes of water that are released slowly in the dry season, maintaining the Delta.

The Delta The Delta receives essentially the same amount of water as river Site 6, in the same pattern of flows described above. Basin development in the Delta, as represented by Site 7, Xakanaxa, would manifest as changes in inundation patterns,

Table 4 Predicted changes in all flow indicators for Site 6 from present day (PD) through the low, medium and high water-use scenarios. Flood types as in Fig. 4.

Flow indicator	PD	Low	Med	High	Comment
Mean annual runoff (10^6 m^3 $year^{-1}$)	9123	8779	8300	6419	Progressive decline: 96%, 91%, 70% of PD
Dry season onset	August	July	July	June	Progressively earlier: 1, 3, 7 weeks earlier than PD
Dry season duration (d)	115	130	145	193	Progressively longer dry season: 2, 4, 11 weeks more than PD
Dry season minimum flow (m^3 s^{-1})	114	101	93	21	Progressive decline: 89%, 82%, 18% of PD
Flood season onset	January	January	January	February	Slightly delayed by 1 week (M) and 2 weeks (H)
Flood season peak (m^3 s^{-1})	620	618	611	573	Progressive very slight decline: 99%, 98%, 92% of PD
Flood season volume (10^6 m^3 $year^{-1}$)	5269	4980	4450	3294	Progressive decline: 96%, 84%, 63% of PD
Flood season duration (d)	150	143	129	103	Progressive shortening of flood season by 1, 3, 7 weeks
Flood type 1: no flood	1	1	1	3	Numbers represent the number of occurrences in the 43-year hydrological simulations. Result shows a progressive shift away from very high floods to lower ones.
Flood type 2: very low	2	2	4	7	
Flood type 3: low	10	10	17	21	
Flood type 4: moderate	19	20	11	3	
Flood type 5: high	2	2	5	8	
Flood type 6: very high	9	8	5	1	

with a predicted major decrease under the high scenario in all major types of permanent swamp (open channels, lagoons and backswamps) and an increase in seasonal swamps (seasonal pools, seasonal sedgeland, seasonal grassland) as well as in dry savannah (Fig. 5). For all vegetation types, the high scenario would show a much greater change than the other scenarios, with almost 80% of the permanent swamp types lost and seasonal swamp types increasing by 104–178% in area. Savannah would show the largest change, increasing by more than fourfold in the high scenario. These shifts would thus represent a significant terrestrialization—drying out—of the northeastern part of the Delta and, as noted earlier, probably more extreme drying-out of the western Delta.

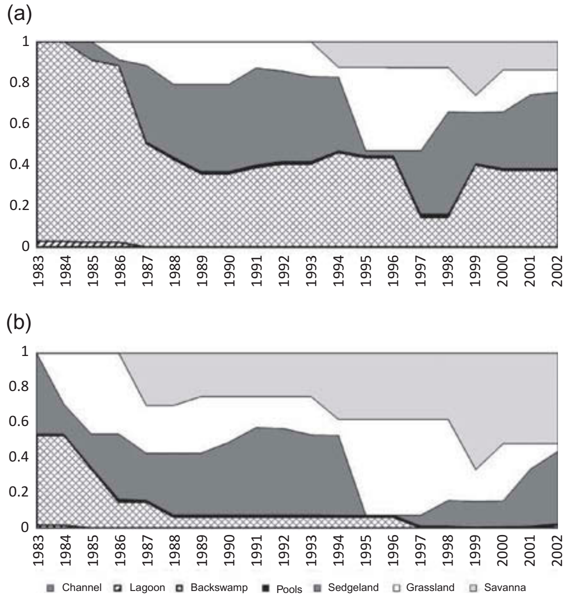

Fig. 5 Time series of vegetation/habitat assemblages at Site 7 in the Delta, showing predicted shifts toward terrestrialization from (a) the present day to (b) the high water-use scenario.

The Thamalakane/Boteti System Development-driven change at Site 8, representing the outflowing Boteti River, would manifest as a progressive decline in the number of years when it contains water. In the high scenario, it would be completely dry for most of the time, holding water only in the wettest years (Fig. 6).

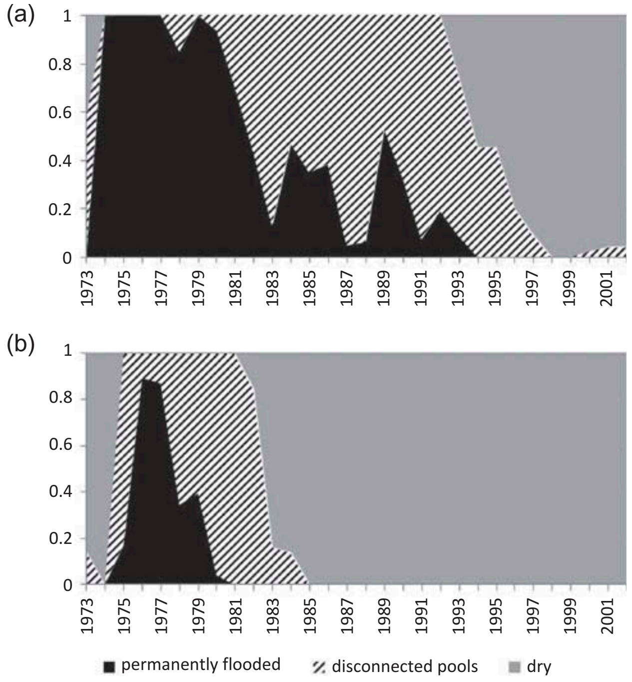

Fig. 6 Time series of predicted flow in the 200-km study reach of the Boteti River (Site 8) under (a) the present day and (b) the high water-use scenario, showing the shift toward drying out.

LINKING THE HYDROLOGICAL, BIOPHYSICAL AND SOCIO-ECONOMIC PREDICTIONS OF CHANGE

In the DRIFT process, the hydrological simulations form the foundation upon which the biophysical and social predictions of change are built. In this project, a time-series version of DRIFT (King *et al*. 2003, King and Brown 2010) was used. Description of what was done has been greatly condensed here to give priority to the hydrological work.

The EFlows team chose 70 biophysical and nine socio-economic indicators (Table 5) that they believe respond to flow changes. Response curves were then compiled that described the relationships between driving and responding indicators. Each response curve described the expected impact of a single type of flow change on the abundance of a single responding biophysical indicator, or of a flow or biophysical driver on a responding social indicator, on a response scale of 0 (no response) to 5 (critically high response) (Fig. 7). A change in flow could thus be followed through to a change in river condition and then on to the resulting social impact. The ratings of change were also converted to percentages (Table 6) for use in some meetings and reports. In total, about 1100 response curves were created for the project and housed in the custom-built DSS.

In the DSS, for each site and scenario, each year’s value for a driving indicator was linked with each response curve that employed that driver, and the corresponding value of the responding indicator was recorded. An indicator such as dry season onset, for instance, would have 43 values from a 43-year simulated flow regime of the calendar week in which the onset occurred. Through a response curve, this would produce 43 annual values for the abundance of, for instance, the indicator “large fish that migrate onto floodplains”.

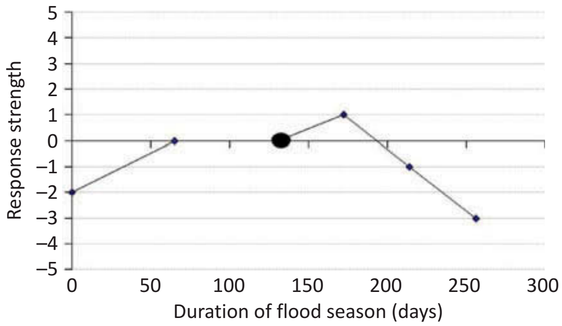

Fig. 7 Example of a response curve: relationship between duration of flood season and abundance of fish resident in the river. The circle indicates median present day (PD) duration of the flood season and the line describes how fish abundance is predicted to increase or decrease in years with longer or shorter flood seasons. Fish abundances are shown (response strength) as comparisons to PD, with PD abundance always shown as zero or 100%.

Table 6 Relationship between response ratings and percentage abundance lost or retained relative to Present Day (PD), used in the interpretation of response curves.

Response rating	Response strength	% Abundance change
5	Critically severe	501% gain to ∞ up to pest proportions
4	Severe	251–500% gain
3	Moderate	68–250% gain
2	Low	26–67% gain
1	Negligible	1–25% gain
0	None	no change (PD)
–1	Negligible	80–100% retained
–2	Low	60–79% retained
–3	Moderate	40–59% retained
–4	Severe	20–39% retained
–5	Critically severe	0–19% retained includes local extinction

Table 5 Examples of indicators used to predict the biophysical and social impacts of development-driven flow changes.

Discipline	Indicator
Geomorphology	Sand bars
Water quality	Conductivity
Vegetation: river	Upper wet bank (trees and shrubs)
Vegetation: Delta	Lower floodplain
Macro-invertebrates	Channel—submerged vegetation habitat
Fish	Large fish that migrate onto floodplains
Birds	Specialists—water lily habitat
Wildlife	Middle floodplain herbivores: elephant, buffalo, tsesebe, warthog
Social: economic	Household income—reeds
Social: lifestyle	Wellbeing from intangible river attributes

The scores from all the response curves for any one indicator were combined in various ways, so that measures of change could be expressed as time series per indicator, per discipline, or as overall ecosystem integrity. For the latter, results were provided on a scale of A to E, where A represented a pristine ecosystem and E a critically modified one with few, if any, intact ecosystem functions and so of little value to people (King and Brown 2010).

ANALYSIS OF THE DRIFT SCENARIOS

Predictions of biophysical change

Five main attributes of the natural flow regime are paramount in supporting the healthy functioning of river ecosystems: the magnitude of flows, their frequency, timing and duration, and the overall variability of flows on every scale from daily to decadal. All of these would be affected by the potential developments, with consequences for the integrity of the river system.

It is predicted that there would be a steady decline in river health from the low to the high scenarios, with the impacts becoming increasingly transboundary (Fig. 8). Although the decline would be localized in the low scenario, it would be felt most severely in the lower basin (the Delta and outflow) in the medium and high scenarios, largely because of their need for strong dry-season flows from upstream. Under the high scenario, large parts of the system would be unable to support present beneficial uses because of significant terrestrialization of the Delta. It is predicted that this would impact severely on the fish, birds and wildlife, with some species declining to as low as 5% of their existing abundances or becoming locally extinct. One group of wildlife—the large herbivores such as elephant, buffalo, tsesebe and warthog—could benefit initially as permanent swamps gave way to seasonal floodplains, but eventually some could also show a decline as wetlands transformed to savannah. Some bird species could similarly benefit in the interim.

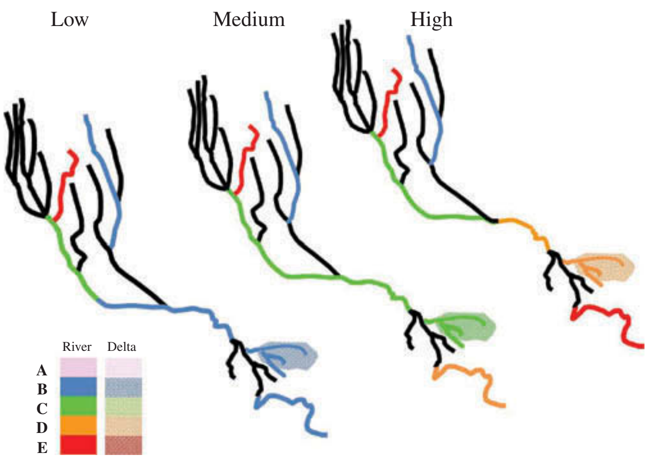

Fig. 8 Summary of expected changes in ecosystem integrity for the low, medium and high water-use scenarios. A: Natural ecosystem; B: Largely natural; C: Moderately modified; D: Largely modified; E: Critically modified. Present-day ecosystem condition is estimated as B. Black reaches were not included in the study. The shading indicates that Site 7 does not necessarily represent the whole Delta.

The decline in river condition is expected to be greater than shown because changes in sediment transport and the impact of fragmentation of the river system by dams (and thus the loss of passage along the river for people, animals and plants) were not included in the work due to lack of data. Catchment and river development, and resulting changes in the sediment dynamics of the river system, could drive major changes in its nature and functioning that could potentially overshadow some of the changes described here. Future data collection and development assessments of the river must address this.

The relationship between ecological condition and flow (Fig. 9) is not straightforward because other factors also affect it. The PD ecosystem condition of the Okavango, for instance, is assessed to be B rather than A, even though flow is very close to natural, because of urban settlements, fishing, poaching and the clearance of riparian vegetation. In general, however, river condition will decline with the loss of MAR and manipulation of flows, and the ecosystem would be likely to become “moderately to largely modified” (Ecological Class C to D), with a concomitant loss of ecosystem services if the MAR dropped to around 70% of natural. This large drop in condition would be due in some places to declining dry-season flows and, in others, such as the Delta, to changes in flooding patterns. The ecosystem could exhibit an even greater decline than shown if the volume of MAR was maintained but the pattern of high and low flows specified in the DRIFT analysis was not adhered to, and as stated earlier, concomitant sediment changes not included in this study could further degrade the system.

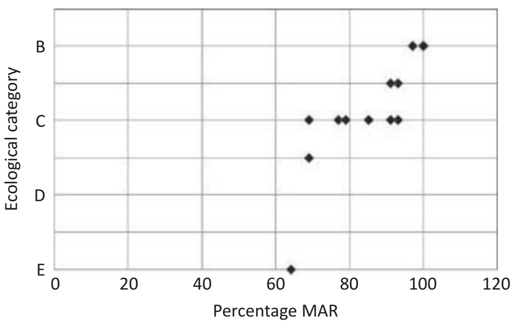

Fig. 9 DRIFT predictions of the category of Okavango ecosystem integrity as a percentage of mean annual runoff (MAR).

Predictions of socio-economic change

The ecosystem changes translate into impacts on the basin's people. River-related livelihoods and national income would decline through the scenarios, with the medium and high scenarios showing a significant decline in both (Fig. 10). This would primarily be as a result of a decline in ecotourism that would severely impact livelihoods and the basin economy. Balancing this against gains from irrigation, hydropower and public water supply, it is predicted that development, as represented by these scenarios, would still show a net loss of up to US$1.4 billion per annum except under unrealistically optimistic economic assumptions. Under such unrealistic assumptions, only the high scenario—which itself is thought to be unrealistic—would show any net gain.

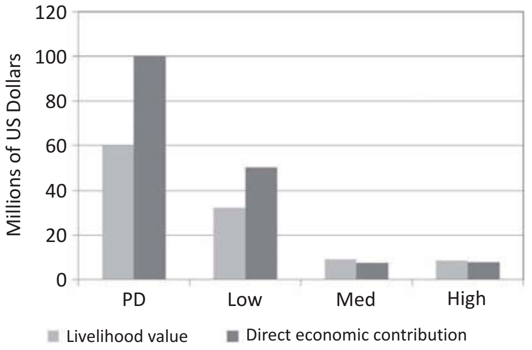

Fig. 10 Short-term implications (in US$ million, 2008) for livelihoods in the Okavango River basin, and direct economic contribution of the river to national income, for present day (PD) and as a result of the three water-use scenarios (OKACOM 2011).

CONCLUSION

Simulated daily hydrological data were the crucial first step in the process of predicting the outcomes of various development pathways for the Okavango basin. Figure 8 does not map an historical decline in a river ecosystem, as it would in so much of the world, but a potential future decline. In doing so, it provides technical information of a nature that has only become available to decision makers in the last two to three decades. It alerts the three Member States to a predicted decline in the condition of their shared resource that would be transboundary in nature and to the basin-wide collaborative planning that would be required to achieve OKACOM's stated objective of "environmentally sustainable regional water resources development".

The concept of Development Space (Fig. 11, King and Brown 2010) could aid such basin-wide planning. Development Space is defined as the difference between current conditions in the basin and the furthest level of development found acceptable to governments and other stakeholders through consideration of the scenarios. Beyond this point, the costs in terms of ecosystem degradation could be

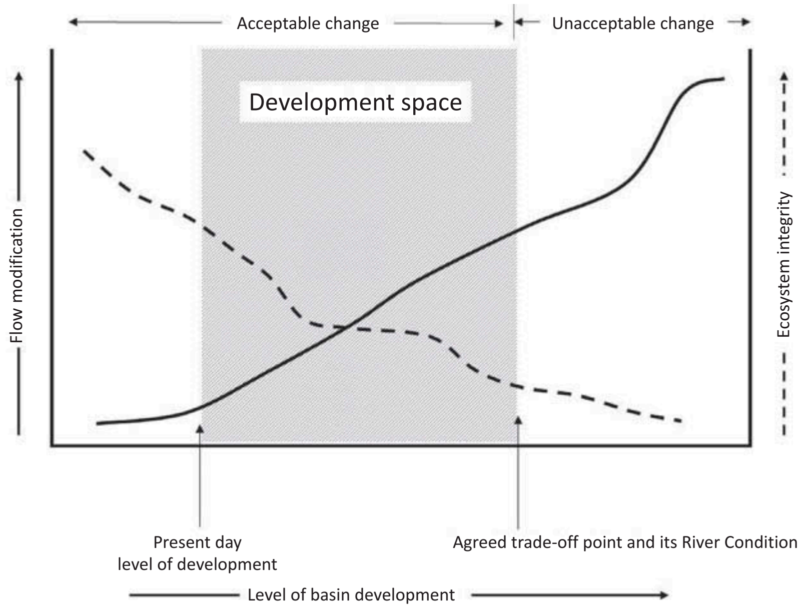

Fig. 11 The concept of Development Space, which is defined by present-day conditions and the negotiated limit of ecosystem degradation as basin development proceeds (King and Brown 2010).

perceived as outweighing the benefits of development.

Delineating the Development Space is essentially a political and social exercise where a trade-off is sought between the costs and benefits of development, the ecological impacts, the implications for rural users of the river and overall local, national and basin interests, to act as the basis of development planning. This is the opposite of historical practice in many basins worldwide where transboundary conflict over water is now increasing. In such historical situations, a need has been identified and then development proceeded, and then another need and another development, and so on, with little or no overall basin planning for managing change and limiting degradation, and thus no focus on the ability of the ecosystem to sustain valued services. The Development Space concept promotes a more modern perspective of water-resource development that consists of first identifying the limit of socially acceptable degradation of an inland water ecosystem and then devising ways of living and developing within that limit; it thus speaks directly to the Millennium Development Goal of ensuring environmental sustainability.

Some of the issues the countries face as they proceed with their negotiations are the following:

- Supplying water and sanitation to those who do not have this would have a modest negative impact on the river ecosystem for a high return in human wellbeing;
- Irrigated agriculture on highly unsuitable soils would have by far the greatest negative impact on the river system;
- The Okavango system is a vital part of the southern African mosaic of wetlands that supports both resident and migrant birds and other wildlife and would need to maintain its ecological status to ensure their long-term viability;
- The scientific team recommended a high development, low water-use future, with little or no development that would affect the natural functioning and size of the Cuito floodplains.

The results form part of the TDA completed for the basin (OKACOM 2011), which in turn was used to develop the SAP. The TDA and SAP have been approved by all three countries at OKACOM level; Botswana and Namibia have approved them at Cabinet Ministers level, and Angola is expected to do this soon (E. Chonguiça, OKACOM Executive Secretary, pers. comm.). Similarly, the concept of Development Space has been accepted by all the countries; Botswana and Namibia have endorsed it at Cabinet level and Angola is in the process of doing so. The main messages from the TDA and SAP are now, *inter alia*, being used in a sustainable development campaign called “My river, my choices” aimed at the basin’s young people aged 12–17.

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APPENDIX

Table A1 The Okavango EFlows team.

Discipline	Specialist
Process management	Jackie King (Process leader) Hans Beuster (Hydrology) Cate Brown (River ecology) Jon Barnes (Social and resource economics) Alison Joubert (DSS designer and data management)
Hydrology	Angola: Manuel Quintino, Paulo Emilio Mendes, Gabriel Luis Miguel Namibia: Andre Mostert, Aune-Lea Hatutale, Mathews Katjimune Botswana: Kobamelo Dikgola, France Tibe
Hydrology advisors	Piotr Wolski, Dominic Mazvimavi, Chandrasekar N. Kurugundla
Geomorphology	Angola: Helder André de Andrade e Sousa Namibia: Colin Christian Botswana: none
Water quality	Angola: Maria João M. Pereira Namibia: Cynthia Ortmann Botswana: Wellington R.L. Masamba
Vegetation	Angola: Amândio Gomes Namibia: Barbara Curtis Botswana: Casper Bonyongo
Aquatic invertebrates	Angola: Filomena Livramento Namibia: Shishani Namutenya Nakanwe Botswana: Belda Q. Mosepele
Fish	Angola: Miguel Morais Namibia: Ben van der Waal Botswana: Keta Mosepele
Water birds	Angola: Carmen Ivelize Van-Dúnem S.N. Santos Namibia: Mark Paxton Botswana: Pete Hancock
Terrestrial wildlife	Angola: Carmen Ivelize Van-Dúnem S.N. Santos Namibia: Kevin Roberts Botswana: Casper Bonyongo
Social/resource economics	Angola: Rute Saraiva, Gabriel Luis Miguel, Paulo Emilio Mendes Namibia: Dorothy Wamunyima, Ndinomwaameni Nashipili Botswana: Casper Bonyongo
Economics	Bruce Aylward