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A comparative review of decision support tools routinely used by selected transboundary River Basin Organisations

H Bukhari[1]* and CA Brown[1,2]

[1] *Southern Waters Ecological Research and Consulting, Cape Town, South Africa*
[2] *University of the Western Cape, Cape Town, South Africa*
**Correspondence: hassan@southernwaters.co.za*

As human pressures on water resources increase, the data and decision support (DS) tools used in the governance, development and management of transboundary rivers are likely to become increasingly important. There are no universal, standardised selection processes or designs for these tools, and so it is up to individual River Basin Organisations (RBOs) to decide what to include in their capacities. This desktop study provides a broad comparative analysis of the suites of DS numerical modelling tools developed and utilised by five intergovernmental transboundary RBOs that advise their member states in the management of their shared water resources: the Permanent Okavango River Basin Water Commission; the Orange-Senqu River Commission; the Nile Basin Initiative; the Zambezi Watercourse Commission; and the Mekong River Commission. These DS tools were reviewed against the information required to enable the kinds of comprehensive assessments of proposed basin management and development plans defined in their respective agreements, which include not only hydrological parameters, but also environmental and social considerations. A review of the model development timelines showed that prior to 2000, little capacity existed in modelling of hydrological, ecosystem, and social components of the river, but that these gaps have been addressed in recent years.

Keywords: ecosystem, model, numerical modelling, sustainable development, water resources, water resources management and development

Introduction

Historically, water-resource development decisions were based mostly on limited engineering and economic criteria (Barrow 1998) and so, for example, often only considered hydropower, irrigation and/or flood control, with little or no consideration of the river ecosystem itself or the social structures it supported (McCully 1996). As concerns over the state of rivers and the consequent impact on people using them grew (Kirchherr et al. 2016), so too did calls to broaden the criteria used to make decisions on how rivers and aquatic ecosystems are used and managed (International Rivers Network 1994; Dubash et al. 2001). Contributing to this is the need to enable 'equitable and reasonable utilisation' through assessment of 'all relevant factors and circumstance' as required by all recent RBO treaties derived from the principles of international water law elaborated in the 1997 UN Convention. In 1997, the World Commission on Dams (WCD) was established to assess the development effectiveness of large dams and, over a period of three years, it conducted a broad review of the global experience with large dams, including evaluation of their technical, financial, economic, social and environmental performance. The WCD final report (WCD 2000) acknowledged the positive role of dams in human development, but recognised the unacceptably high (and largely unanticipated) negative social, economic and ecological impacts of many large dams. The WCD called for comprehensive impact and risk assessments to accompany all future dam development, and for five core values: equity; efficiency; participatory decision-making; sustainability; and accountability to underpin water-resource decision-making (WCD 2000). WCD (2000) was met with some resistance, and none of its recommendations have been officially accepted by major international financial institutions, or many national governments (Fujikura and Nakayama 2009). Gradually, however, environmental and social criteria started to be included in water-resource planning and decisions on new dams; particularly following the publication of the Millennium Development Goals (MDGs) and their successors, the Sustainable Development Goals (SDGs; United Nations General Assembly 2015). These provide a structured array of considerations pertaining to social justice and ecosystem health that had not previously been part of water-resource decision making. Inclusion of environmental and social considerations is also supported by the core principle in international water law of 'equitable and reasonable utilisation' requiring assessment of 'all relevant factors and circumstances', which is reflected in the treaties/agreements of the five River Basin Organisations (RBOs) considered here. This led to the adoption by RBOs of a suite of new methods and tools aimed at providing decision-makers with information on how proposed developments might affect the rivers and their allied social structures. The methods and tools included ones from the fields of ecohydrology (e.g. Guedes

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et al. 2016), ecohydraulics (e.g. Newson 2002; Maddock et al. 2013), Environmental Flows (EFlows; e.g. Dyson et al. 2008; Forslund et al. 2009), resource economics (e.g. Albrecht et al. 2018; Shaw 2005) and sociology (e.g. Tilt et al. 2009).

Governance and decision-making in transboundary rivers are of concern as human pressures on water resources in one country may lead to damage to aquatic ecosystems and consequential loss of ecosystem services in another, for example, flood protection, recession agriculture, and fisheries (Pröpper et al. 2015). This is particularly true for systems on which large numbers of people depend, such as those in Africa and Asia. In such regions, the challenge is to help balance the drive to meet national development goals and promote social equity, while safeguarding the livelihoods of rural people across the whole basin and protecting an increasingly degraded environment (United Nations General Assembly 2007) within the ethos of international cooperation.

The objective of the international agreements for cooperative management and development of transboundary RBOs is framed around the cornerstone principle of international water law, that being '…equitable and reasonable utilisation …with a view to attaining optimal and sustainable utilisation thereof and benefits therefrom…' (UN Convention on the Law of the Non-navigational Use of International Watercourses; United Nations General Assembly 1997). Most transboundary RBOs have an advisory function, focussing on promoting cooperation and dialogue and supporting processes of joint planning as outlined in their respective agreements. The challenges in doing this are recognised in the Vision Statements of many of the RBOs (Table 1) designed to promote transboundary cooperation and sustainable development.

To meet such Vision Statements, it is imperative that the information used to inform governance, planning and decision making in the basins expands beyond the engineering and economic criteria that underpinned such endeavours in the past to include criteria that capture the relevant aspects of social justice and environmental health (Timmerman and Langaas 2005; McCartney 2007). Recognition of the need to include such information has led to strong investment by many transboundary RBOs, and their international funding partners, in data management systems and Decision Support (DS) tools to inform better and more sustainable development planning. Initially, these comprised rainfall-runoff and water-resource models, financial models, and hydraulic and routing models, but increasingly they have included models addressing the broader issues of sustainability in a river basin, such as water quality, sediment supply and transport, land use, agricultural productivity, environmental flows and ecosystem functioning, biodiversity, direct links between people and the river ecosystems, and social wellbeing. The information generated by these tools is important globally, but arguably more so in developing countries where hundreds of millions of people are subsistence users of rivers, with livelihoods that are dependent on naturally functioning, healthy river ecosystems (Kahl 2008); and where much of the world's new water-resource development is currently occurring (Zarfl et al. 2015).

This desktop study is a comparative analysis of the suite of DS tools adopted by five inter-governmental RBOs that provide advice to the member states in the management and development of their shared water resources (Table 2; Figure 1). With the focus of the review being on Africa, four of these (the Permanent Okavango River Basin Water Commission [OKACOM], the Orange-Senqu River Commission [ORASECOM], the Zambezi Watercourse Commission [ZAMCOM] and the Nile Basin Initiative [NBI][1]) are African. The fifth, the Mekong River Commission (MRC), is in south-east Asia. The Vision Statements for the basins managed by these RBOs highlight the need for sustainable development that balances social justice, ecosystem integrity and economic prosperity (Table 1). Thus, the DS tools used by each RBO were evaluated in terms of their ability to provide the kind of information needed to make balanced decisions in line with these visions.

Approach

The approach adopted was to compile a short-list of the kinds of information required to advise on decisions that aligned with the basin Vision Statements in their respective international agreements. Thereafter, information on data management and DS tools used by each RBO was collected using official websites, on-line library facilities, research registers and search engines. Keywords included, basin name +: model discipline (such as hydrology, water-resources, fish, EFlows), assessment, SDGs, sustainable, basin study, strategic plan, and integrated water-resource management. Only models and spreadsheets with direct links to the relevant RBO were included; others, such as those used for academic research, or not applied by or on behalf of the RBO, were excluded even though they may be useful. Email requests for information were also sent to ~15 RBO representatives and colleagues active in the RBOs, and the requested documentation was received in almost every instance. The efficacy or accuracy of the various DS tools was not assessed. Although this is an important consideration, it was beyond the scope of the current study.

The DS tools documented by the RBOs were reviewed against the sort of information needed to evaluate whether or not development and management proposals were in line with the social and environmental provisions in their Vision Statements. The SDGs (United Nations General Assembly 2015) were used to guide to the kind of information needed. Based on the SDGs, for social justice or quality of life (Table 1) metrics are required for the basin that predict or measure whether development and/or management initiatives would, *inter alia*, alleviate poverty (SDG 1), reduce hunger (SDG 2), promote sustainable agriculture (SDG 2), well-being (SDG 3) and gender equality (SDG 4), and improve access to safe water, sanitation (SDG 6) and energy (SDG 7; after Stockholm Resilience Centre 2017). For environmental health, information is needed on how development and/or management initiatives would affect the health of river ecosystems (SDG 6 and 15), combat

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[1] Note: NBI is not yet a formal RBO established by treaty amongst the Member States.

Table 1: Examples of Vision Statements for transboundary river basins

RBO	Vision Statement	Date
Nile Basin Initiative (NBI)	To achieve sustainable socio-economic development through the equitable utilization of, and benefit from, the common Nile Basin water resources (NBI 2021a)	1999
Niger Basin Authority (NBA)	The Niger Basin, a shared region of sustainable development achieved through the comprehensive, integrated management of water resources and their associated ecosystems, to improve everyday living standards and prosperity by 2025 (NBA 2007)	2005
Mekong River Commission (MRC)	An economically prosperous, socially just, environmentally sound [and climate resilient] Mekong River Basin (MRC 2021a)	ca. 2005
Lake Chad Basin Commission (LCBC)	Lake Chad and other wetlands maintained at sustainable levels to ensure the economic security of the freshwater ecosystem resources, sustained biodiversity and aquatic resources of the basin, the use of which should be equitable to serve the needs of the population of the basin thereby reducing the poverty level (LCBC 2008)	ca. 2008
Orange-Senqu River Commission (ORASECOM)	A well-managed water secure basin with prosperous inhabitants living in harmony in a healthy environment (Haasbroek 2014)	2014
Zambezi Watercourse Commission (ZAMCOM)	A future characterised by equitable and sustainable utilisation of water for social and environmental justice, regional integration and economic benefit for present and future generations (ZAMCOM 2021)	ca. 2014
Permanent Okavango River Basin Water Commission (OKACOM)	Economically prosperous, socially just and environmentally healthy development of the Cubango-Okavango River Basin (OKACOM 2018)	2015
International Commission for the Congo-Ubangui-Sangha Basin (CICOS)	An integrated region, where united and emergent nations develop their capacities in order to make water a key driver for economic growth and a source of wellbeing, while preserving the quality of ecosystems, as well as adapting its uses to climate change and encouraging cost and benefit sharing (CICOS 2014)	2015
International Commission for the Protection of the Danube River (ICPDR)	Cleaner, healthier and safer waters for everyone to enjoy (ICPDR 2016)	ca. 2016
Great Lakes Commission (GLC)	Ensuring the Great Lakes and St. Lawrence River support a healthy environment, vibrant economy, and high quality of life for current and future generations (GLC 2017)	ca. 2017

climate change (SDG 13) and protect and restore aquatic and other ecosystems (SDG 14 and 15).

An indicative timeline of model development was also developed for each RBO, and advances in flood forecasting were recorded. Lastly, as participatory decision-making should include the generation, as well as the sharing, of information (WCD 2000), the online data and information sharing services of each RBOs were rated qualitatively in terms of the number of reports and datasets available online and ease of access.

Decision support tools needed

Assessment of all relevant factors and circumstances requires evaluation of the ecological and social implications, and thus incorporation of areas of study and expertise previously excluded from water-resource and other planning in river basins, such as sociology, gender studies, resource economics and EFlows. The tools used in these disciplines differ from the engineering and economic tools traditionally used, and they require different kinds of expertise and data to populate them, and to monitor outcomes (Table 3).

Tools developed/adopted by RBOs

Development of numerical modelling decision support tools for the transboundary RBOs in this paper was not common before 2000. Between 2000 and 2005, development focussed almost entirely on regional hydrology, for example, the development of rainfall runoff and water balance models, through the Soil and Water Assessment Tool (SWAT) and the Integrated Quantity and Quality Model (IQQM) at the MRC and the initiation of the Southern African Development Community-Hydrological Cycle Observing System (SADC-HYCOS) project (a hydrology and weather data collection and data exchange framework supported by the World Meteorological Organization), and water-resource models to balance supply and demand. By 2020, all RBOs had developed water-resource and hydrology models, and progress had been made on other disciplines, although some gaps remain (Figure 2).

Three approaches emerged to developing Decision Support System (DSS) capacity in the RBOs: NBI and ZAMCOM opted for a Single provider (Danish Hydraulic Institute; DHI). ORASECOM adopted the tools used by one of the Member States (South Africa); and MRC and OKACOM have a range of specialised models, developed by different groups.

The NBI undertook a period of intense model development between 2010 and 2015, during which time they calibrated many of the models needed to support the Vision for the Nile (Figure 2; Table 4). NBI implemented the MIKE HYDRO model (with river and basin modules that together cover river hydrology, hydraulics, water quality and water resource related modelling requirements) and a series of custom scripts to calculate social (including food security, water security, health security, income security,

Table 2: RBOs included in the review

RBO	MRC	NBI	OKACOM	ORASECOM	ZAMCOM
Basin	Lower Mekong[1]	Nile	Cubango-Okavango	Orange-Senqu	Zambezi
Basin area	795 000 km^2	3 176 541 km^2	530 000 km^2	973 000 km^2	1 395 171 km^2
Basin Population	60 million people	257 million people	900 thousand people	19 million people	32 million people
Mean Annual Runoff	16 000 $m^3 s^{-1}$	2 830 $m^3 s^{-1}$	475 $m^3 s^{-1}$	365 $m^3 s^{-1}$	4 134 $m^3 s^{-1}$
Established	1995	1999	1994	2000	2014
Member States	Cambodia, Lao PDR, Thailand, and Viet Nam	Burundi, DR Congo, Egypt, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda. Eritrea is an observer.	Angola, Botswana, and Namibia	Botswana, Namibia, Lesotho, and South Africa.	Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia, and Zimbabwe
Secretariat Location	Lao PDR	Uganda	Botswana	South Africa	Zimbabwe
Website	mrcmekong.org	nilebasin.org	okacom.org	orasecom.org	zambezicommission.org
DS tools	MRC DS Framework (DSF)	Nile Basin DSS	CORB DSS	None listed	ZAMWIS-DSS
Data management system	MRC Data and Information Service Portal	Nile Information System (Nile IS)	None listed	Orange-Senqu Water Information System (WIS)	Zambezi Water Resources Information Systems (ZAMWIS)

[1] Downstream of the Laos/Myanmar border

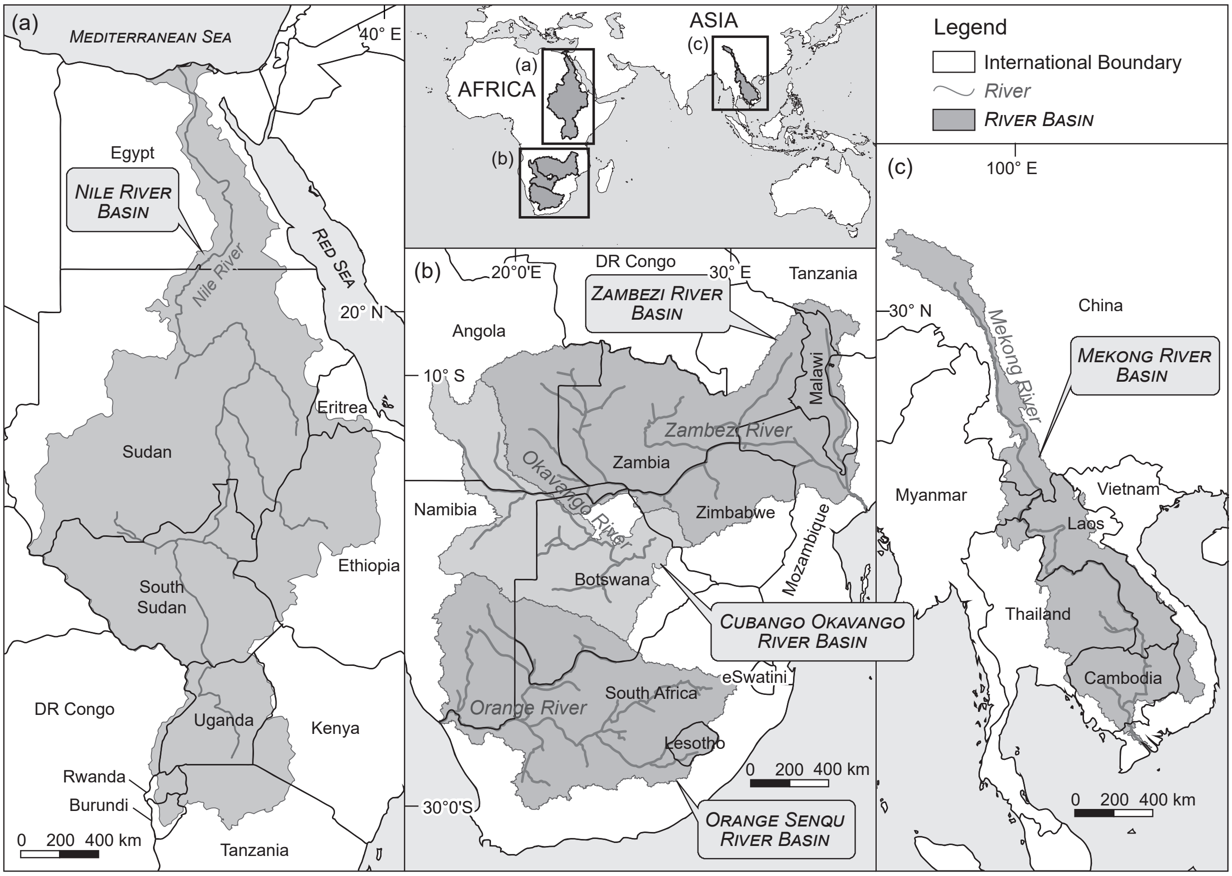


Figure 1: Maps showing the location of the Nile River Basin (a), the Orange Senqu, Zambezi, and Cubango Okavango river basins (b), and Mekong River Basin (c) (Lehner et al. 2008; Lehner and Grill 2013)

Table 3: Basic data required to evaluate ecological and social implications of development

Disciplines	Description
Hydrology	Surface water flow simulations, linked to basin runoff and proposed developments. Some hydrological models are also used as water-resource models.
Water resource models	Estimates of water usage and allocation based on water availability, reservoir capacity and abstraction volumes for agricultural, municipal, and other uses.
Geohydrology	Groundwater-flow simulation, linked to basin runoff and developments.
Hydraulics	Simulation of depths, velocities and areas of inundation linked to daily/hourly hydrological time-series and elevation profiles.
Sediments	Simulated sediment supply linked to basin runoff and proposed developments.
Water quality	Simulations of water quality parameters, such as temperature, dissolved oxygen, salinity and nutrients linked to basin runoff and developments.
EFlows	Methods and tools for decisions on the volume and pattern of flows needed to support ecosystem functioning. Some EFlows tools are also social models.
Aquatic ecosystem good and services	Interactive eco-social models, linked to hydrological/hydraulics times-series.
Farming and natural resource use	Models or spreadsheets that link productivity of farmland and availability of other natural resources, such as fish, sand or reeds, to hydrology, water quality, sediment delivery.
Resource economics	Economic models that compare the net present value of the use and development of natural resources often with a focus on the water, food, and energy nexus.
Social wellbeing	Social indicators of river dependant populations linked to the physical environment, such as health to water quality, and incomes to fishing and natural resource use.
Equality	Statistical models or spreadsheets that track the distribution of benefits arising from developments or management options.
Flood forecasting	Models that predict flood forecasts through hydrological, weather, and satellite data and communicate them in terms of flow volumes, water levels, and extent of inundation.

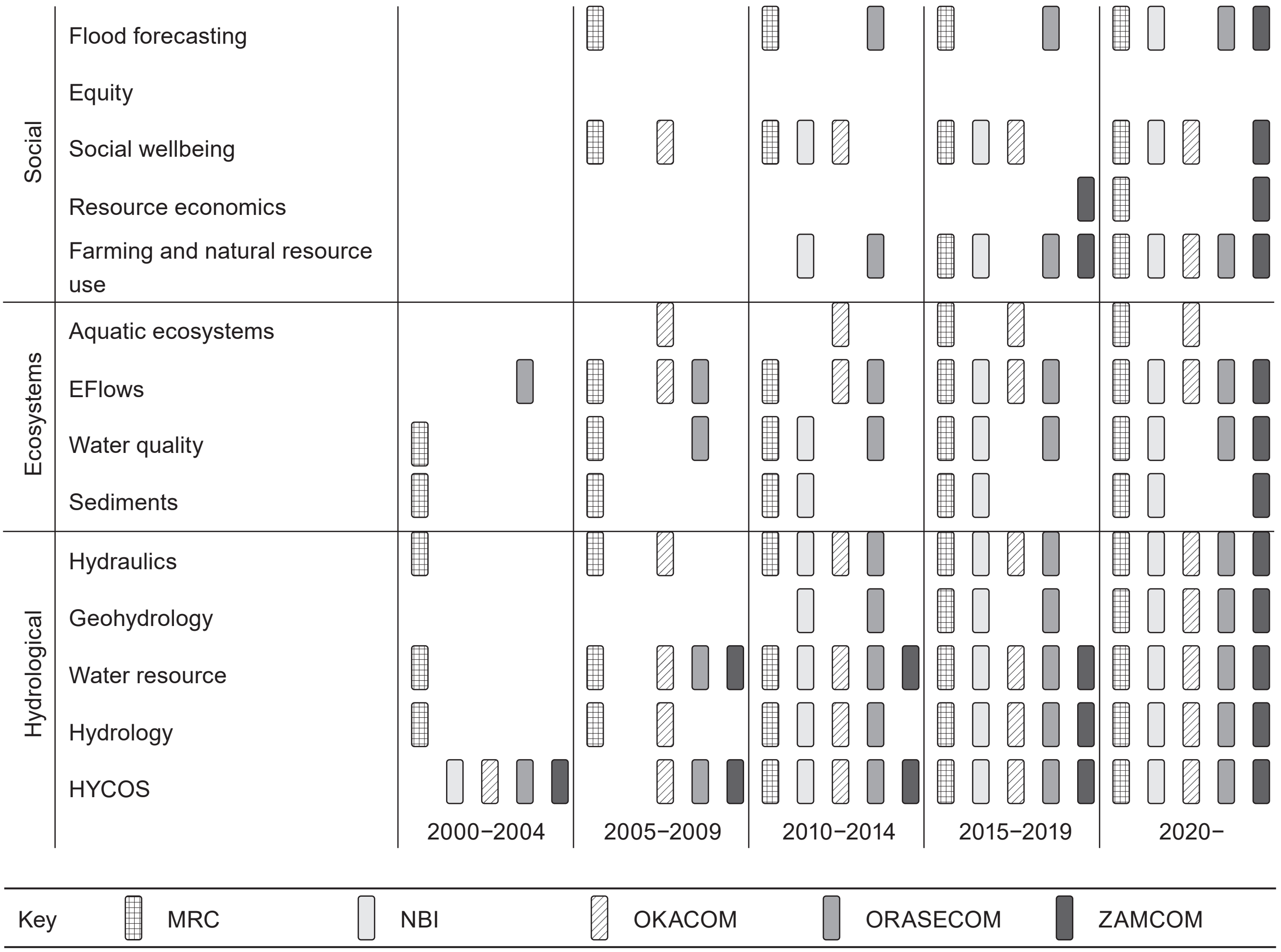


Figure 2: Models and indicative timeline of development used in the five RBOs

employment, and gender), economic and environmental indicators. These form the core of the NBI DSS. The NBI DSS also contains MIKE SHE for more detailed hydrological modelling, including groundwater, and MIKE 11, which is an older version of MIKE HYDRO. A coarse basin-scale EFlows assessment was conducted in 2018 using PROBFLO (O'Brien et al. 2017; NBI 2018) with the goal of supplementing the aquatic ecology modelling capabilities in the NBI DSS (NBI 2015b, 2018).

In common with NBI, ZAMCOM implemented the MIKE HYDRO model in 2018 (ZAMCOM 2018); although a water resource model (using US Army Corps of Engineers - Hydrologic Engineering Center [HEC-3] software) was developed for the basin earlier (ZAMCOM 2010). The initial MIKE HYDRO installation is currently being upgraded, including the addition of DRIFT-equations to supplement its aquatic ecology modelling capabilities (Brown et al. 2013; Southern Waters 2019). The final capabilities of the upgraded model are not known, but are likely to be similar to the NBI DSS, as it is being developed by the same group. The Strategic Plan for the Zambezi River Basin (ZAMCOM 2019a) also set up a full suite of separate modelling tools for the basin. These included CLIRUN-Wet to simulate monthly rainfall runoff, AquaCrop to calculate agricultural productivity, the water-resources model, Water Evaluation and Planning (WEAP), and the Water, Hydropower, Agriculture Tool for Investment and Financing (WHAT-IF), which values the use of water by the agricultural, domestic and hydropower sectors (ZAMCOM 2019b).

ORASECOM adopted a suite of South African modelling tools used by the Department of Water and Sanitation (DWS). The tools were set up and used to support the Orange-Senqu Integrated Water Resources Management Plan in three phases ending in 2007, 2011 and 2014 (ORASECOM 2021). They include the Water Resources Simulation Model 2000 (WRSM2000) for rainfall runoff and hydrological modelling set up in 2011 (Haasbroek et al. 2011), and water-resource models, the Water Resource Yield Model (WRYM) and the Water Resource Planning Model (WRPM), set up in 2014 (ORASECOM 2014). The Water Quality Total Dissolved Solids (WQT) model is used to calculate total dissolved solids, phosphate, and chlorophyll-a loads and concentrations (ORASECOM 2015). Eco-hydraulic parameters are calculated through HEC-RAS, which was set up for the selected sites on the Orange River and the Molopo Wetlands in 2010 (Birkhead

Table 4: Models used by the reviewed RBOs. Black shading indicates that the model is a core component of routinely used DSS or was used in a major basin study. Grey shading indicate model is in development. Xs indicate model was introduced but does not appear to have gained traction

Name	Description	MRC	NBI	OKACOM	ORASECOM	ZAMCOM
Hydrology						
CLIRUN-WET	A monthly rainfall runoff model (ZAMCOM 2019b)					■
HBV	A rainfall-runoff model that includes conceptual numerical descriptions of hydrological processes (SMHI 2019)	X				
IQQM	A generic integrated water quantity and quality simulation model (Simons et al. 1996)	■				
MIKE HYDRO River	A hydrology model with a 1D river hydraulic component. It can also calculate water quality and sediment transport		■	■		▒
NAM	A deterministic, lumped, and conceptual rainfall-runoff model (NBI 2015a) used by MIKE HYDRO		■			▒
Pitman Model	A monthly rainfall runoff model (Seago 2016)			■		
SWAT	A basin-scale rainfall-runoff model used to simulate the quality and quantity of surface and ground water (SWAT 2021)	■		▒		
VMod	A grid-based distributed hydrological model that is used to compute discharge and water quality in river basins (MRC 2018c)	X				
WRSM2000	A hydrology model developed for South Africa. Includes algorithms for surface water/groundwater interactions (Middleton and Bailey 2005)				■	
Water Resource						
HEC-3	A river and reservoir system model (ZAMCOM 2010)					X
MIKE HYDRO Basin	A multipurpose water resource and allocation model that contains inbuilt hydrology and reservoir operation tools		■			▒
Source	A daily time step water balance model used for water resource management. (eWater 2021)	■				
WRYM	A monthly stochastic yield reliability model used to provide scenario-based historical firm and stochastic long-term yield (Seago 2016)				■	
WRPM	Uses yield reliability to determine water supply volumes based on storage, operating rules, user allocation rules (Seago 2016)				■	
WEAP	A water-balance model (WEAP 2021)			■		■
CLI-OPT Screening Tool	A screening and optimization tool that can run multiple scenarios through the WEAP model (ZAMCOM 2019b)					■
Geohydrology						
MIKE SHE	An integrated hydrology model that can simulate surface and groundwater flows and surface water/groundwater interactions		■			▒
MODFlow	A finite-difference flow model, used to simulate ground water			▒		
WRSM2000	The enhanced WRSM 2000 includes estimates for ground water storage level and outflows, and surface and groundwater interactions				■	
Hydraulics and Hydrodynamics						
EIA 1D/2D/3D	A hydrodynamic model suitable for advanced 3D and coupled 1D/2D/3D surface water modelling (MRC 2018b)	■				
HEC-RAS	A 1D steady flow hydraulic model designed for channel flow analysis and floodplain determination (Tate 1999)				■	
ISIS	A 1D hydrodynamic model used to evaluate water level, sediment, nutrient, and salinity values (MRC 2018b)	■				

Table 4: (cont.)

Name	Description	MRC	NBI	OKACOM	ORASECOM	ZAMCOM
JFLOW+	A 2D hydraulic model that simulates flood risk including river, coastal and dam break floods (JFlow 2021)	▨				
MIKE 11	1D hydrodynamic model that simulates water quality and sediment transport (NBI 2015a)		■			
Mike HYDRO River	Successor of MIKE 11 with a graphical user interface (NBI 2015a)		■			▨
Okavango Delta Inundation Model	Custom 2D models for modelling inundation or flood extents in the Okavango Delta and Boteti River (Wolski et al. 2006)			■		
Sediment						
ISIS	Simulates sand transport and changes in bed profile	■				
EIA 1D/2D/3D	A hydrodynamic model used to assess the transport and reactions of sediments, nutrients or other substances	■				
MIKE HYDRO	A hydrological model can be used for basic sediment transport modelling		■			▨
Water Quality						
IQQM	A generic integrated water quantity and quality simulation model (Simons et al. 1996)	■				
Mike HYDRO River	A hydrology model with basic advection-dispersion module that includes a simple decay function but no other water quality processes		■			▨
Source	The model can assess in-stream water quality through water quality routing and in-stream constituent decay	■				
Water Quality TDS Model	Used for modelling the concentration of total dissolved solids and sulphates in the water resource system (Nkwonta et al. 2017)				■	
EFlows						
HFSR method[3]	Integrates hydrological, hydraulic and habitat data to predict the impacts of a changing flow regime on ecosystem condition				■	
Estuary Method[2]	EFlows assessment method for estuaries				■	
IBFM	Response of ecosystem indicators to changes in flow regime	X				
PROBFLO	Regional scale ecological risk assessment of the social and ecological consequences of altered flows (O'Brien et al. 2017)		■			
NBI DSS custom scripts (environment)	Predicts the response of 15 ecologically relevant indicators to flows, water quality and project footprints (NBI 2015b)		■			
DRIFT Eco-Social Model	Predicts the response of aquatic ecosystems and linked social systems to changes in flow, sediment, infrastructure and management	■		■	■	▨
Aquatic Ecosystem Goods and Services						
DRIFT Eco-Social Model	Comprehensive modelling and development scenario analysis of the entire river basin ecosystem and linked social systems	■		■		
Farming and Natural Resource use						
AquaCrop	Simulates yield response of herbaceous crops to water (Mejias and Piraux 2017)	■				■
Custom Scripts (irrigation)	Uses GIS database and remote sensing to calculate present day and future irrigation water demand				■	
EIA 3D	Calculates floodplain, coastal, and lake fishery production by linking it to flooding, alluvium transport, and primary production (MRC 2018b)	■				
NBI DSS Custom scripts (economic)	Custom scripts calculate 10 economic indicators by linking them to flows, hydropower operation, and agricultural production. (NBI 2015b)		■			

[3] Set flow regimes linked to Ecological Categories (Kleynhans 1996) that rate the ecosystem degradation from A to F.

Table 4: (cont.)

Name	Description	MRC	NBI	OKACOM	ORASECOM	ZAMCOM
Resource Economics						
WHAT-IF	Uses surface water availability and water demand projections and evaluates economic gains of water allocation (ZAMCOM 2019b)					■
MerSim Spreadsheet Models	Socio-economic model uses hydropower, fishery and agricultural output data to value the use of natural resources (AWP 2019)	▨				
Social						
MerSim Spreadsheet Models	Calculates 22 social indicators by linking them to parameters, such as water availability, water quality, flooding and others (Smajgl 2019)	■				
NBI DSS Custom scripts (social)	Custom scripts calculate 15 social indicators by linking them to flows, water quality and project footprints. (NBI 2015b)		■			
WUP-FIN Policy Model	A Bayesian causal network model of the environmental social economic system of the Tonle Sap Lake (Varis 2003)	X				
Forecasting						
Flood and Drought Monitor	Uses rainfall forecasts and a rainfall runoff model to forecast floods		■			
Flood Forecasting and River Monitoring	Provide 5–day flood forecasts through Streamflow Synthesis and Reservoir Regulation model and multiple regression models	■				
Mike HYDRO River	Provides 90–day flow and water level forecasts using an integration of measured flow data and rainfall forecasts					▨
DWS Models	Near real-time stage, flows and rainfall for stations in the Orange-Vaal system, plus routed hydrographs showing actual and predicted stage				■	
SAR FFGS	Hydrological response of small basins to rainfall as estimated in near real time by information from weather radar and satellite systems			■	■	■
MRC FFGS	Forecasts on floods based on estimated rainfall in small catchments	■				

Acronyms used in the table include: Decision support system (DSS); Department of Water and Sanitation (DWS); Downstream Response to Imposed Flow Transformations (DRIFT); Environmental Impact Center of Finland (EIA); Flash Flood Guidance System (FFGS); Habitat Flow Stressor Response (HFSR); Hydrologic Engineering Center (HEC); Hydrologiska Byråns Vattenbalansavdelning (HBV); Integrated Basin Flow Management (IBFM); Integrated Quantity and Quality Model (IQQM); Mekong Region Simulation (MerSim); Mekong River Commission (MRC); Nedbør-Afstrømnings-Model (NAM); Nile Basin Initiative (NBI); River Analysis System (RAS); Soil and Water Assessment Tool (SWAT); Southern African Region (SAR); Water Evaluation and Planning System (WEAP); Water Resource Planning Model (WRPM); Water Resource Yield Model (WRYM); Water Resources Simulation Model (WRSM); Water, Hydropower, Agriculture Tool for Investment and Financing (WHAT-IF)

2010) and for the Orange River Estuary and the Fish River in 2013 (Louw et al. 2013a). ORASECOM used the Habitat Flow Stressor Response Method (HFSR) to set prescriptive EFlows for the Orange River and Estuary (Louw et al. 2013b). The EFlows assessments for the upper parts of the catchment were done under the auspices of the Department of Water Affairs (DWA; for the Vaal sub-basin; DWA 2009, 2012) and the Lesotho Highlands Development Authority (LHDA; for the Senqu sub-basin; Brown et al. 2008) using HFSR and DRIFT, respectively. Lastly, custom scripts were developed to estimate irrigation water demands. As far as this review could establish. ORASECOM does not have models to evaluate social wellbeing or equity indicators.

In the MRC, the Soil & Water Assessment Tool (SWAT; Rossi et al. 2009) is the main hydrological model (Table 4) and is used to generate daily sub-basin runoff and sediment, nitrogen and phosphorous yields from rainfall, soil, land use and elevation data. SWAT was first set up for the Lower Mekong Basin (LMB) in 2001, together with the Integrated Quantity and Quality Model (IQQM; for water resources and water quality) and the ISIS model for hydraulics (World Bank 2004; MRC 2021b). Since then, the MRC has undertaken several major updates of the data used in SWAT (MRC 2018a), including modifications and plug-ins required to synchronise it with Source (eWater 2021), which supplemented IQQM in 2018 (MRC 2018b). The outputs from SWAT are fed into IQQM/Source, which generate daily hydrological time-series at key locations. ISIS uses the outputs from SWAT and IQQM to calculate mainstream hydraulics and evaluates tidal influences, flow reversal in the Tonle Sap River, and water level, velocity and inundated area along Mekong mainstream and Mekong Delta (MRC 2018b). Between 2000 and 2008, the EIA 1D/2D/3D model (3D-EIA; also colloquially referred to as the WUP-Fin model because it was developed under the Water Utilisation Programme funded by the Finnish Government) was developed for the three-dimensional hydraulic modelling deemed necessary to fully capture the intricacies of flow reversal in the Tonle Sap Lake (MRC 2007). The developers of 3D-EIA also introduced the HBV (Hydrologiska Byråns

Vattenbalansavdelning; MRC 2007) hydrology model and the VMOD hydrological model, which they preferred over SWAT/IQQM combination, as well as social and policy models, but these do not appear to have gained traction. This period also yielded the Integrated Basin Flow Management Model (IBFM; MRC 2009), which predicted the response of the aquatic ecosystems to proposed developments. The Council Study (2014–2017) saw the refinement of many of these models, including the hydrodynamics of Tonle Sap and the Mekong Delta (3D-EIA; MRC 2018b, 2018c), the set-up of the DRIFT-BioRA Eco-social Model to predict aquatic ecosystem and ecosystem services responses (Brown et al. 2013; MRC 2017), and the development of series of custom scripts addressing irrigation (AquaCrop), and socio- and macroeconomics (Mekong Region Simulation; MerSim; Smajgl 2019). The MRC adopts a biophysical approach to predicting impacts on natural resource use, such as farming and fishery production. The 3D-EIA and AquaCrop uses biophysical inputs (e.g. flooding extent, alluvium transport and primary production for 3D-EIA; weather, soil characteristics for Aquacrop) to generate values for fishery and crop yields. Projected fishery yield calculations are adjusted using DRIFT BioRA, which provides the likely biomass of various fish species under different development scenarios. MerSim connects modelled outputs (such as agricultural produce and fish catch, flooding extents and hydropower generation) to social indicators defined around water availability, community health and safety, food security, livelihoods and displacement. More recently, the US Army Corps of Engineers (USACE) has been assisting the MRC with summarising the outputs of the Council Study into the public participation tool, Shared Vision Planning (SVP; GWP 2018), which provides a forum for stakeholders to identify trade-offs and options.

OKACOM has followed a DSS development path similar to that of the MRC. In ca. 2009, under the Food and Agricultural Organization funded Transboundary Diagnostic Analysis (OKACOM 2011), the Pitman hydrological model (Pitman 1973); the Water Evaluation and Planning model (WEAP 2021), a water-resource accounting model; and the DRIFT Eco-Social Model (King et al. 2014) were setup for the Cubango Okavango River Basin (CORB). The Okavango Delta Inundation Model (Wolski et al. 2006; Wolski and Murray-Hudson 2008) and an early hydraulic model of the ephemeral Boteti River, both of which were developed by the Okavango Research Institute (ORI; then Harry Oppenheimer Okavango Research Centre) at the University of Botswana, were also included in the suite of assessment tools. In common with the MRC process, these models were later updated in 2016–2017, as part of the Multisectoral Investment Opportunity Analysis (MSIOA; OKACOM 2017), and have recently been upgraded again, as part of the EU Technical Assistance Programme (EU 2020) and the USAID Resilient Waters Programme (USAID 2019). SWAT linked to MODFlow is also being set up for the basin, as part of the work around the development of the CORB Fund (OKACOM 2019). Creation of a dashboard to link these models is part of ongoing work being conducted under the EU Technical Assistance Programme (Simon Johnson, Technical Director at JG Afrika, pers. comm.).

Numerous other DS tools have been developed for the basins discussed here, but these were developed outside of the context of the RBOs' work plans, without the requisite participation and agreement from all member states, and have not been incorporated into the DSSs routinely used by the RBOs. Examples include the Vietnam Ministry of Natural Resources and Environment's proportional model that relates sediment supply and whitefish yield (Yoshida et al. 2020) and the SWAT model setup for the Blue Nile (Ali et al. 2014). Individual projects, such as strategic environmental assessments (SEAs) or development planning initiatives, also routinely introduce new models and tools into the basins that are not necessarily incorporated into the DSSs used by the RBO; these are not covered here.

The descriptions of the tools and their capabilities were reviewed against their ability to provide the social and environmental information needed to make decision in line with the RBO Vision Statements, as guided by the selected SDGs (Table 3; Table 5). In general, the DSS tools in the RBOs represent a fairly good coverage of the data required to evaluate ecological implications of development (Table 3; Table 5) and all, to a greater or lesser extent, appear to be able to run scenarios to evaluate future impacts linked with basin developments and/or climate change. Some DSSs, such as those of the MRC and OKACOM, can also model management actions, such as restricting fishing seasons or the type of gear used. There are some noticeable gaps, however. For instance, from the information available to this review, the ZAMCOM does not feature social issues, such as welfare or equity, in their current suite of DS tools, although their agreement and Vision Statement explicitly mentions economic benefit for present and future generations (Table 1). The MRC, NBI and OKACOM reported that they have tools to calculate the implications of development plans for social indicators, such as social welfare, community health and food security. Many of the RBOs do not have a full suite of economic, engineering and financial tools, possibly because these tools are vested with Member States, who undertake detailed water-resource and other planning for their sovereign territories. Finally, most of the prediction capabilities of the social and environmental tools were restricted to the main river and major tributaries, and coverage of smaller tributaries and sub-basins was poor in all of the RBOs reviewed.

Operating the complex tools developed by the MRC, OKACOM and ORASECOM remains the domain of technical experts. Nevertheless, these DS tools have played a central role in generating data and information to support the development of basin studies. As discussed above, such studies include the Orange-Senqu Integrated Water Resources Management Plan in 2011 and 2014 (ORASECOM 2021); the Study on Sustainable Management and Development of the Mekong River (The Council Study; MRC 2018b) and the Mekong River Basin Development Strategy (MRC 2021b); the Okavango MSIOA (OKACOM 2017) and more recent Programme for Transboundary Water Management (EU 2020). NBI (2015c) highlights projects from five member countries that used the DSS to generate data to support the development of integrated water resource plans, flood control, and water permitting systems for local basins. These studies demonstrate that 1) DS tools used in the past have been used, and sometimes

Table 5: Summary of matchup between the capability of the RBO DSS tools and Vision Statements. Black shading = Tools can test SDG; Grey shading = Limited capacity to test SDG

RBOs	Subset of social SDGs (SRC 2017)				Subset of environmental SDGs (SRC 2017)					
	Goal 1. No poverty	Goal 2. No hunger and sustainable agriculture	Goal 3. Ensure healthy lives and promote well-being	Goal 5. Gender equality and empower women and girls	Goal 6. Water and sanitation for all	Goal 7. Affordable, reliable, sustainable and modern energy	Goal 6. Water and sanitation for all (Sustainable management of)	Goal 13. Combat climate change and its impacts	Goal 14. Conserve and sustainably use life below water	Goal 15. Protect, restore and sustainably use ecosystems
MRC	▒	▒	▒		▒	▒	■	■	■	■
NBI	▒	▒	▒		▒	▒	▒	▒	▒	▒
OKACOM	▒	▒	▒		▒	▒	■	■	■	■
ORASECOM	▒	▒			▒	▒	▒	▒	▒	▒
ZAMCOM	▒	▒			▒	▒	■	▒	▒	▒

improved upon, in subsequent assessments and 2) the information generated by these tools has been presented to stakeholders and decision makers. How this information has been received and or used is beyond the scope of this paper. In many cases, the decisions regarding river management and development have yet to be made.

Forecasting

All of the RBOs have also invested in flood forecasting systems intended to provide early warning about impending floods to communities in flood-prone areas, in an effort to limit property damage and loss of life. Flood forecasting is dependent on accurate real-time hydrometeorological data for the river system (Clark 1994). The MRC, for instance, has invested in numerous real-time hydrological monitoring stations combined with satellite data to predict flood events (Table 4). Access to real-time data is, however, an issue in many developing countries, where 66% of hydrometeorological observation networks are in a poor or declining state (World Bank and GFDRR 2018). ORASECOM uses the South African and Namibian government hydrometric stations, for which near real-time are posted on-line (www.dws.gov.za/Hydrology/Default.aspx), as well as projected stage and discharge in the Orange and Vaal rivers, based on data for stations in the upper catchment (DWS 2021). The NBI use the Flood and Drought Monitor tool (DHI 2021), based on the Global Forecast System weather forecast model (NOAA NCEP 2011), which provides global real-time and forecast data on temperature, wind, precipitation and soil moisture. OKACOM, MRC and ZAMCOM have developed flash flood warning systems using the World Meteorological Organization (WMO) Flash Flood Guidance System (FFGS). These are based on frequent localised rainfall forecasts from weather radar (e.g. South African Weather Service weather radar systems; Poolman et al. 2015) and/or weather satellite (e.g. NOAA/NESDIS Operational Global Hydro Estimator and Meteosat weather satellite; WMO undated; Poolman et al. 2015) systems and modelled rainfall-runoff responses of individual sub-basins (Georgakakos 2018).

Spatial distribution of models

The existence of a social or environmental model in the RBO toolkit does not mean complete spatial coverage of the basin. Most tools deal only with the main stem and major tributaries. One reason for this is a lack of hydrological and other data for the smaller tributaries. For instance, ZAMCOM has done some work in the Shire and Kafue tributaries, but its main focus is the mainstem Zambezi River.

Higher granularity and spatial extent provide for more complete assessments and the need for detailed small-catchment hydrology is being addressed in some basins. For instance, in the CORB, the resolution of the Pitman Model has recently been increased (from 24 to 31 subbasins; OKACOM 2021) and SWAT is being set up for ~200 sub-basins (Tracy Baker, The Nature Conservancy, pers. comm.), however, this increased resolution has as yet not been extended to the eco-social models. Similarly, the PROBFLO EFlows model set up for the Nile River does not extend to the Nile Delta (Figure 3). Non-, or incomplete, involvement by countries that share the river basin can

Figure 3: Spatial distribution of PROBFLO assessment sites on the Nile River

Figure 4: Spatial distribution of DRIFT-BIORA assessment zone in the Lower Mekong River. There are five zones along the main Mekong River, plus one each covering the Tonle Sap River, Tonle Sap Lake and the Mekong Delta

also be a limiting factor. In the case of the MRC, China and Myanmar are observers, rather than Member States, although they comprise a significant (and upstream; 22% by area) portion of the catchment (Figure 4).

Not all assessments in a basin are done simultaneously, partly because some parts of the river, such as headwaters, floodplains and estuaries require different approaches. Thus, it is fairly typical for assessments to be extended to other parts of the river quite some time after the first assessments were completed. The EFlows assessments for the Orange Senqu (Figure 5), for instance, were done in five phases over nearly 20 years: (1) Senqu Sub-basin – DRIFT (LHDA 2002; LHDA 2003; Brown et al. 2008); (2) Vaal Sub-basin – HFSR (DWA 2009; DWA 2012); (3) Orange River main stem – HFSR (Louw and Koekemoer 2010; Louw et al. 2013c); (4) Molopo Sub-basin – HFSR (Louw and Koekemoer 2010); (5) Fish Sub-basin – HFSR (Louw et al. 2013d) and the Orange River Estuary – Method (Louw et al.

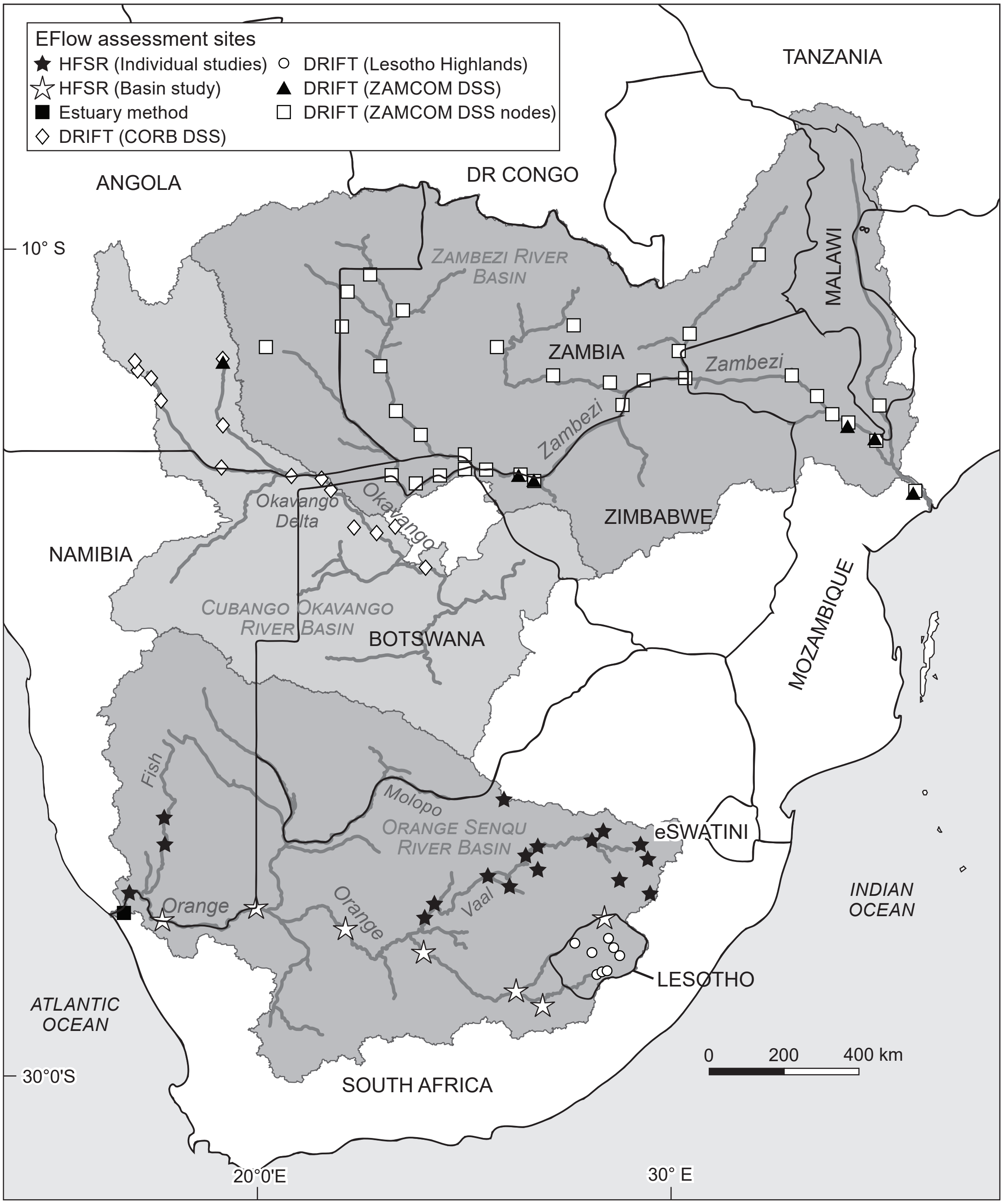


Figure 5: Spatial distribution of EFlows assessment sites in the Orange, Cubango-Okavango, and Zambezi River basins

2013e). For ZAMCOM, the EFlows equations currently being incorporated into the ZAMCOM DSS suite were compiled from four separate DRIFT studies completed at different times: (1) the Lower Zambezi and Zambezi Delta (Beilfuss and Brown 2010); (2) the Middle Zambezi (Southern Waters 2014); (3) the Elephant Marshes on the Shire tributary (Birkhead et al. 2016); (4) and the Upper Zambezi (Birkhead 2018); plus data from similar rivers in adjacent basins. Some 30 locations on the Zambezi River and its tributaries (Figure 5) were categorised into six hydro-ecological groups (Rosgen 1994; Rowntree 1999) and the data from the representative sites where studies had been done were extrapolated across the basin. Both the MRC and OKACOM have also updated and extended the spatial scope of early EFlows assessments as the information generated by these became more mainstreamed in decision-making.

Accessibility of data, information and DS tools

Appropriate data and information availability are important for the effective management of transboundary rivers (Timmerman 2005) and for the transparency that engenders trust between Member States (Schreiner et al. 2011). Data and information sharing are stated goals of all of the RBOs reviewed in this study. Other than OKACOM, which provides for data sharing through information resource centres in each Member State, the RBOs have dedicated data and information sharing portals: the MRC Data and Information Service Portal; the Nile Information System (Nile IS), Orange-Senqu Water Information System (WIS), and the Zambezi Water Resources Information Systems (ZAMWIS). In their own words, the MRC invites users to ‘explore our data-rich research, analysis, toolkits’; NBI describes the Nile IS as a ‘web based state of the art tool that supports the systematic storage, organization, retrieval and dissemination of relevant NBI generated technical reports’; ZAMCOM describes ZAMWIS as an ‘interactive web-based data and information portal’, and ORASECOM says its WIS ‘provides searchable documents, data, media and software’ and ‘supports data and information sharing between ORASESOM riparian states’.

To assess the degree to which these claims are met, the data and information sharing capabilities of the RBOs were rated qualitatively in terms of the quantity, organisation and searchability of their publications and data using the qualitative scoring system shown in Table 6.

The MRC website has the greatest array of features and scored highest across all the data and publication sharing indicators (Figure 6), with ZAMCOM and ORASECOM next highest. ZAMCOM has an almost complete array of features but some are incomplete. ORASECOM was rated high on the quantity of the data shared, but these data are difficult to locate and tend to be highly technical. The other RBOS have a wide array of documents on their website, but the data sharing capabilities are either limited or absent.

The MRC Data and Information Service Portal stands out in terms of the quantity (over 400 publications and 10 000 datasets), user-friendly search and filtering options, and the presentability of the data, which can be viewed online via charts, graphics and maps, and can be downloaded in clean and easy to use MSExcel® worksheets. ZAMWIS also contains a large number of documents (373 total files including maps, factsheets and reports) and custom search features, but these were not as user-friendly as those of the MRC. The links for the NBI IS and the NBI Library, which together comprised NBI’s main data and information sharing services, were not functional throughout the writing of this paper; and only limited information (65 documents and no datasets) is available on the NBI website. Similarly, the OKACOM website presents ~50 documents including reports, newsletters, videos, and photographs. The Orange Senqu WIS is organised by project with available publications and data listed on each project page (42 projects listed with ~100 documents). The data made available are difficult to access due to their non-explanatory file naming, non-standard file formats (some of which required specialised software to open), absence of guidance notes or manuals, and poor presentation.

The DSS tools employed by the RBOs were also mostly not available to the public, although there were some exceptions. The NBI DSS can be downloaded from the NBI website (NBI 2017) once a licence has been obtained from the NBI Secretariat. NBI also provides a free online course on the NBI DSS (NBI 2021b) and a publicly accessible DSS community support forum. ORASECOM also shares some project-related tools. For instance, the Irrigation Classification Tool for the Irrigation Water Demand Management project (Chidley et al. 2011) is available for downloading.

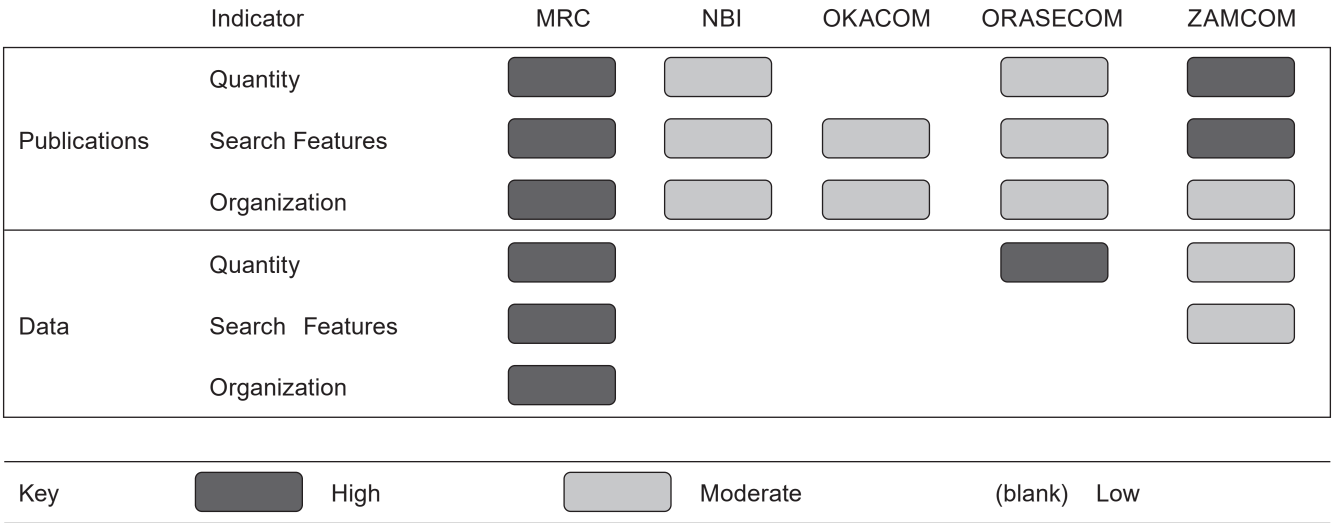
Discussion

If the vision statements for the basins assessed in this paper, and the corresponding international agreements reflected in their respective treaties, are to be achieved, it is important to be able to model and quantify criteria pertaining to social justice and ecological integrity alongside the engineering and economic prospects of development and/or management initiatives (McCartney 2007). Without this information, it is not possible to know whether proposals align with the visions, or will lead to a move away from one or more stated aims. As they are required to do so under their respective agreements/treaties and under the key principles of international water law, all the RBOs recently reviewed in this paper have made considerable progress in delivering this kind of information to their Member Countries; although there are some gaps and the extent to which the information is used to make decisions on the future of the transboundary basins represent remains unclear. The most noticeable gaps are modelling capacity for disaggregating genuine in-basin costs and benefits for different stakeholder or community groups, and calculations of equity. The paucity of spatial coverage is also of concern, as many of the developments planned and the restorations efforts required, are found in tributaries, and so these should be covered by the models.

The experience of the RBOs reviewed here, shows that development of the required DSS capacity is an iterative and ongoing process. After an initial investment in generating eco-social data, almost all RBOs either revised their tools or developed new ones, and may well do so again. Some of the tools that are now used in the RBOs did not exist a decade ago, others were rudimentary, and so it is expected that they will develop and improve,

Table 6: Qualitative scoring system used to rate data and information sharing capabilities

Area	Indicator	Scoring		
		High	Moderate	Low
Publications	Quantity	Over 250 documents	Between 50 and 250 documents	50 documents or less
	Search Features	Document specific search	Generic sitewide search	No search capacity
	Organization	Detailed classification by Type, Topic, Function, Language	Basic classification into type of document	Poor or no organization
Data	Quantity	Over 50 datasets	Less than 50 datasets	No datasets are shared
	Search Features	Data specific search	Generic sitewide search	No search capacity
	Organization	Detailed classification	Basic classification	Poor or no organization



	Indicator	MRC	NBI	OKACOM	ORASECOM	ZAMCOM
Publications	Quantity	■	□		□	■
	Search Features	■	□	□	□	■
	Organization	■	□	□	□	□
Data	Quantity	■			■	□
	Search Features	■				□
	Organization	■				

Key ■ High □ Moderate (blank) Low

Figure 6: Comparison of Data and Information Sharing Services of each RBO through the RBO website or online WIS. Refer to Table 6 for the qualitative scoring system used to rate the data and information sharing capabilities into high, moderate, and low level of attainment categories

as the demand for the information generated increases. Opportunities abound for other RBOs to learn, and possibly leapfrog, in the development of their own capacity. Similarly, having started with modelling on the main stem river and major tributaries, most of the RBOs reviewed are now looking to expand the spatial coverage of their DS tools to provide the granularity needed to improve decision making. Technical advances in remote sensing and monitoring are also improving the quality and granularity of the data available, thereby enabling better predictions of the impacts of proposed management and development activities within the basins.

Major challenges are: translating complex multi-disciplinary assessments using the DS tools into a form that decision-makers can effectively utilise in determining and agreeing on investments and management strategies; data exchange in transboundary waters (Mukuyu et al. 2020), particularly those related to ecological impacts and social equity; and technical capacity in numerical modelling and maintaining a core group of modellers to support the RBO.

Future work should also seek to answer whether the existence and use of these DS tools and models leads to better decisions on water-resource development, and specifically to better social and environmental outcomes. It seems likely that systematic data collection supporting these DS tools, if it is occurring, also only started recently, which makes answering questions related to these aspects difficult, due to the limited years of observational data post their application. This emphasises the importance and urgency of pursuing this line of research. Similarly, incorporation of monitoring data to improve the predictive capacity of the DS tools is essential, but at this stage appears to be infrequent, at best. Incorporation of near-real time data and automated updates is perhaps the next frontier for transboundary DSS capabilities.

If basin vision statements are to be effectively operationalised, it is imperative that each aspect covered by them is systematically evaluated, based on the best available knowledge, and used to inform decisions on development and management. If this is done, it is possible to set the targets that these initiatives must achieve. Those that do not meet the standards set should be reconceived in terms of their location, design, operation or distribution of benefits, so that they meet the standards, or discarded. This paves the way for innovation, and ensures that only approaches aimed at achieving the whole of the vision are pursued. Thereafter, it is equally important that the outcomes are monitored against the vision, as part of a broader adaptive management process.

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