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Sudd Wetland Monograph – Volume 4: Environmental Flows Assessment

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The purpose of the technical report series is to support informed stakeholder dialogue and decision making in order to achieve sustainable socio-economic development through equitable utilization of, and benefit

from, the shared Nile Basin water resources.

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ABBREVIATIONS

AQ	Aquatic Vegetation
BIRDS_ECO_POT	Ecological importance of migratory and resident birds
BN	Bayesian Networks
BN-RRM	Bayesian Networks Relative Risk Model
CPT	Conditional Probability Tables
e-flows	Environmental flows
FISH_ECO_POT	Ecological importance of fish
FISH_SUBS_DEMAND	Demand for fisheries
FR	Fringe Vegetation
GR	Grasslands
GRZ_DEMAND	Demand for Grazing
INVERT_ECO_POT	Ecological importance of aquatic invertebrates
MAR	Mean Annual Rainfall
NAV_DEMAND	Demand for navigation
NBI	Nile Basin Initiative
OW	Open Water
PA	Papyrus Marsh
RE	Reed beds
RR	Risk Region
RRM	Relative Risk Model
SC	Scenarios
SUB_AGRIC_DEMAND	Demand for vegetation for subsistence
TR	Trees and shrubs
VEG_ECO_POT	Ecological importance of vegetation
WD_POT	Potential threat of water disease to people

1. INTRODUCTION

1.1 Overview

Floodplains are complex water resources that develop from interactions between water and sediment, physical structures and biological processes in the landscape (Opperman et al, 2017). These ecosystems have enormous ecological, cultural and economic value (Opperman et al, 2017). These ecosystem services include sediment and nutrient reduction, carbon sequestration, groundwater recharge, fisheries, recreation and support for biodiversity but often traditional management of floodplains leads to the reduction in these ecosystem services. Effective and sustainable management of floodplains requires understanding of the fundamental hydrological processes of the floodplain and associated river systems (Opperman et al, 2017). Consequently, the determination of the environmental flows (e-flows) required to sustain and maintain floodplains is vital for their optimal management.

Environmental flows are defined as the "*quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being*" and aims to recover aquatic biodiversity, ecosystem integrity and important ecological services by managing freshwater flow regimes (Arthington et al, 2018). This concept was included in the vision for environmental flow management in the Nile Basin as the vision objective is described as "*to achieve sustainable water resources development through management of the Nile Basin's flows required to sustain the freshwater and estuarine ecosystems and the human livelihoods and wellbeing that depend on these ecosystems*" (NBI 2016a). To determine e-flows, various methods have been developed by the international community including best practice e-flow assessment and management principles and frameworks that take into consideration both social and ecological features of an ecosystem on a regional scale, incorporating risk evaluation and uncertainty (O Brien et al, 2018). Such a methods is PROBFLO which was developed as a Bayesian networks relative-risk model (BN-RRM). It is a scenario-based e-flow assessment tool that uses a probabilistic modelling approach that addresses uncertainty to evaluate the socio-ecological consequences of altered flow regimes but taking cognizance of the synergistic effects of the non-flow drivers on the ecosystem (O Brien et al, 2018). This method was used to establish the e-flows for the Sudd wetland in the Nile Basin in South Sudan and evaluate the socio-ecological effects of the altered flow in the study area.

Study area

Sudd is an Arabic word that means barrier or blockage, describing the islands and large floating mats of vegetation that make up the wetland (NBI, 2012). The Sudd wetland is the second largest wetland area in the world and is located in southern Sudan and forms part of the Bahr el Jebel system (NBI, 2012; Rebelo and El-Moghraby, 2016). Some of the wetland is permanent and some seasonal which makes the size of the overall wetland variable, between 57 000 km^2 and 130 000 km^{2,} depending on the season. The wet season spans April till October and the dry season November to March with most of the water that enters the Sudd wetland, circulating within it and evaporating and does not contribute to the outflow at Lake No (Rebelo and El-Moghraby, 2016). This is an important element of the hydrologic cycle as the evaporated water is transformed into rainwater and the increase in air moisture results in less evaporation during the dry season (NBI, 2016).

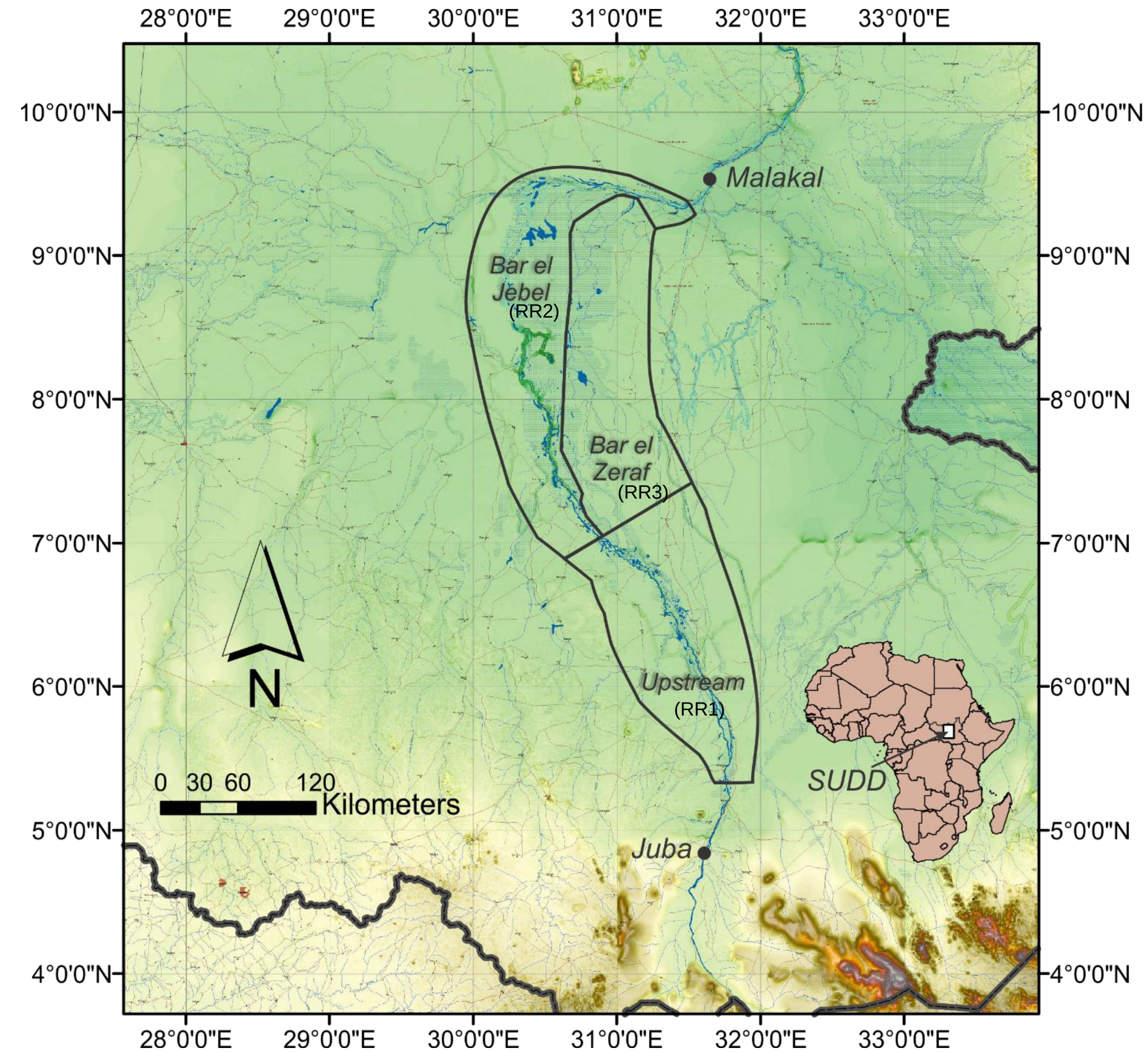

Figure 1: Map of the SUDD wetland in Africa and the delineated risk regions

The Sudd wetland is diverse of which 5.7 million hectares was declared a Ramsar wetland site of international importance in 2006 (Rebelo and El-Moghraby, 2016). It consists of open water, submerged vegetation, floating fringe vegetation seasonally inundated woodlands, rain-fed and river-fed grasslands, and floodplain scrubland which all contribute to the high biodiversity of the Sudd (Rebelo and El-Moghraby, 2016). Many of the habitats are still intact and unaffected and provides essential habitat for migratory birds and antelope as well as fish, aquatic plants and invertebrates (NBI, 2016b, Rebelo and El-Moghraby, 2016). This includes the world's largest concentrations of shoebills (*Balaeniceps rex*) and Nile lechwe (*Kobus megaceros*), as well as 274 other bird species and 78 species of fish (NBI, 2016a).

It is estimated that over one million people are reliant on the Sudd wetland in the form of food, freshwater, building material, grazing, navigation and medicinal products (NBI, 2016b). The socio-economic benefits of the Sudd wetland are immense with the total economic value (TEV) for the year 2015 set at approximately $3.3 billion per annum (NBI 2020). 8% of the TEV is from provisioning services, 37% from biodiversity and 55% from regulating services like microclimate regulation, flood control and water regulation (NBI, 2020). Anthropogenic activities that pose a threat to the wellbeing of the Sudd include oil exploration and extraction within the Sudd wetland and the completion of the Jonglei Canal. Oil exploration and extraction may result in disruption of water flow patterns, wetland and floodplain fragmentation, high salt concentrations in the water, reduction in vegetation cover, dying livestock and uncommon diseases experienced by local communities (NBI, 2016b; Rebelo and El-Moghraby, 2016). This will ultimately lead to a reduction in wetland biodiversity, especially fish species which will result in a loss of food security for the local communities. Other water contaminates is the overuse of agrochemical for agricultural production as this may lead to the eutrophication of the wetland (NBI, 2016b).

The construction of the proposed Jonglei Canal started in 1980, with the intention to divert inflows into the Sudd wetland thus reducing evaporation that occurs in the wetland and provided more water to downstream users (Rebelo and El-Moghraby, 2016). With the completion of the canal, 100 000 ha would be reclaimed for agricultural use and the water level of the swamp would drop by 10% in the wet season and 20% in the dry season. This would result in significant impacts on climate, groundwater discharge, sedimentation, water quality biodiversity, grazing areas, seasonal migration patterns as well as the livelihoods of local communities. Construction on the canal stopped in 1983 due to civil war, after 260 km of the 360 km was completed and the future completion of the canal is unknown (Rebelo and El-Moghraby, 2016).

The aim of this study is to establish the quantity and timing of freshwater flows into the Sudd Wetland to provide water levels in the wetland necessary to sustain aquatic ecosystems and evaluate the socio-ecological consequences of altered flows using PROBFLO. This report presents the PROBFLO approach adopted to reach the aim and the e-flow for the Sudd Wetland.

The Sudd wetland is of great socio-ecological importance to the residents of the wetland and the upstream and downstream beneficiaries of ecosystem services provided by the Sudd. This includes but is not limited to the regulatory services of the wetland and provisioning services where the highly productive wetland provides local and regional residents of the Nile basin with fish and other products from the wetland. This process of e-flow determination (part of the Sudd Monograph series on "Nile Basin wetlands of transboundary significance: Inventory, Baseline Study and Framework Management Plan with a nested case study on the Sudd") has been produced using social and ecological information from the other monograph reports to demonstrate the application of and e-flow determination approach which has been undertaken in the Sudd Wetland as a part of NBI's efforts to support South Sudan in the process of establishing the necessary knowledge/baseline information sustainable resource management.

1.2 Purpose and Development

This "Volume 4 – Environmental flows assessment" is the 4th and last of a 4-part series and a supplementary volume to the Sudd Monograph, a key output of the NBI's Wetlands Programme support to South Sudan through the South Sudan's Wetlands Working Group, which aims to develop a comprehensive information and knowledge base on the existing conditions of the Sudd that can be used as an aid by decision makers to help guide future planning and development initiatives. Supplementary volumes follow with specific focus on detail aspects such as hydrological modelling, TEEB and environmental flows. These documents will be important sources from which to reference critical information that is required to ensure sound management of the Sudd.

Volume 1 – Sudd Wetlands Monograph

Volume 2 – Sudd Eco-Hydrological Planning Model

Volume 3 – The Sudd Economics of Ecosystems and Biodiversity

Volume 4 – The Sudd Environmental Flows Assessment

The development of the Sudd Monograph has been based on active and sustained stakeholder engagement by consulting with local government officials, NGOs and local communities. Additional consultative meetings and discussions were held with officials from national and regional agencies. This approach enabled the use of significant local expertise and knowledge to understand local issues, challenges, and solution opportunities. The development of the Sudd Monograph can thus be seen as a collaborative effort among NBI and the Sudd stakeholders at regional, national, and local levels.

1.3 Outline of the Report

This report consists of the following chapters:

Chapter 1 gives a brief overview, outlining the purpose of the document and how it has been developed.

Chapter 2 provides the methodology that was followed to conduct the environmental flows assessment in the Sudd.

Chapter 3 shows the results of the environmental flows assessment

Chapter 4 ends the report with a conclusion

2. METHODOLOGY

The study area includes the whole of the Sudd wetland, from where the Bahr el Jebel enters the wetland at Mongalla to the outflow at Malakal (Figure 1). The PROBFLO approach (O Brien et al, 2018) was implemented to determine the e-flows and risk of various alternative water resources management scenarios for the Sudd wetland and the ten procedural steps (Figure 2) that are briefly explained below. Consider how this approach has been adapted for application from traditional river approach to the Sudd wetland (BOX 1).

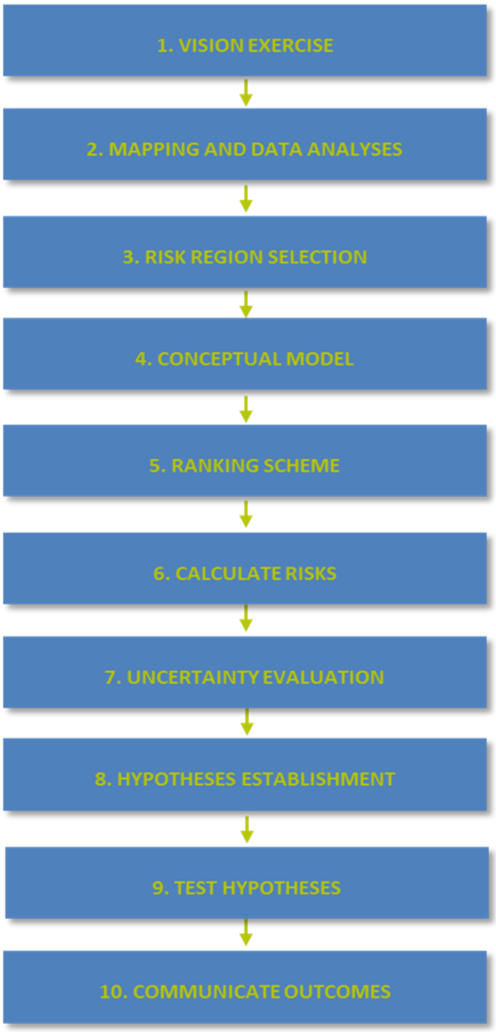

Figure 2: Ten procedural steps for PROBFLO (O'Brien et al, 2018)

Step 1 included the establishment of a vision for the Sudd wetland and resulted in the selection of social and ecological endpoints. The social endpoints were associated with the maintenance of the livelihoods of local communities and the ecological endpoints, the biodiversity and ecosystem processes of the wetland. A literature review of the study area formed part of Step 2 and maps were established of the wetland and other water resources and associated ecosystem services. To allow for the ecosystem dynamics and endpoints to be evaluated in a relative and spatial manner (Step 3), the study area was divided into three geographical risk regions (Figure 1). In Step 4, the causal risk pathways between identified sources to stressors and socio-ecological receptors in multiple habitats to endpoints were demonstrates as conceptual models with a ranking scheme established to represent the condition of each variable and the risk to each endpoint (Step 5). Microsoft ® Excel was used to calculate the risk (Step 6) and NeticaTM was used to construct the BN and determine the distribution of risk ranks that represent the risk profiles for each endpoint. These outcomes were then combined through multiplication of random assignments of risk ranks into meaningful integrated social or ecological risk probability distributions for each risk region using Monte Carlo procedures undertaken with Oracle® Crystal Ball™ software. The use of these randomisation evaluations is also used to quantify the effects of parameter uncertainty on the risk predictions (Landis, 2004), with sensitivity evaluation procedures in Netica™ for uncertainty testing in this assessment (Step 7). A monitoring plan/programme is required to examination the validity of the risk assessment (Step 8), which is tested by the implementation of management and the plan/programme and (step 9). The final step of the approach (Step 10) is to communicate the outputs of the risk assessment and generate good practice recommendations for future sustainable management and risk mitigation.

BOX 1
APPLICATION OF PROBFLO IN WETLANDS:

In this case study, fundamental differences between rivers and wetlands has necessitated some changes in the application of the holistic e-flow approach PROBFLO. Lets start with some tricky definitions: The Ramsar Convention's definition of wetlands includes a wide range of surface inland ecosystems including; "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres" (Ramsar Convention Secretariat 2011). But within this definition, wetlands (*usually specified as a palustrine wetland)* can also be defined as transitional ecosystems between aquatic and terrestrial systems, and are generally characterised by (permanently to temporarily) saturated soils and hydrophytic vegetation. These areas are, in some cases, periodically covered by shallow water and/or may lack vegetation. In this case a river can be classified as different to a wetland being a 'lotic' aquatic ecosystem with flowing water concentrated within a distinct channel, either permanently or periodically, and different from an "open waterbody" which is a permanently inundated 'lentic' aquatic ecosystems where standing water is the principal medium within which the dominant biota live. Using this definition an open waterbody like a lake, must have a maximum depth greater than 2 m and have limnetic (lake-like) characteristics (Ollis et al., 2013). The NBI defines wetlands as "those areas (or ecosystems) that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support a prevalence of vegetation typically adapted for life in saturated soil conditions". This definition of a wetland includes swamps, flood plains, seasonally flooded grasslands, the edges and shallow waters of rivers and lakes, estuaries and coastal marshes and mangroves and peat bogs. Here you can see that there are some major fundamental differences between open ended rivers, which are formed in the upper reaches of a catchment and generally flow into an estuary and into an ocean.

E-flows represent the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, livelihoods, and well-being. (Brisbane declaration of environmental flows, 2018). Based on this definition e-flows of wetlands relates to the levels of flows requires in a wetland to meet the ecological requirements of the system. Here's where there are some fundamental differences in the application of PROBFLO to determine e-flows for the Sudd wetland. The Sudd wetland has a defined spatial area within the Nile Basin. When e-flows are determined for rivers a semi-qualitative approach is adopted for the entire system, to determine e-flow requirements of a range of reaches of the rivers being considered, which are then to aligned to determine holistic e-flows for the river. For the Sudd wetland a qualitative approach must be adopted where the entire ecosystems has be modelled as one unit that receives input flows from the White Nile River (and direct precipitation and groundwater contributions). In this case study the water being delivered to the Sudd from the White Nile River is required to meet the e-flow requirements of the Sudd. While it is impossible to represent the entire river (which in the case of the Nile River case is >6500km) in an e-flow case study, due to the longitudinal nature of rivers and consideration of their structures and functions sites/reaches can be used to represent different parts of rivers and determine e-flow requirements for the entire ecosystems. Because wetlands exist in spatially confined areas, and generally do not have longitudinally comparable features, for holistic e-flow assessments, the entire system has to be modelled, with quantitative (rather than qualitative or semi-qualitative) relationships used to represent socio-ecological system components. In this case study the semi-qualitative measures for indicators have been replaced with qualitative ones that can be used to evaluate the socio-ecological consequences of changes in the area (m^2) and associated depths (m) of wetland habitat inundated by altered upstream (White Nile River) flows.

2.1 Vision

The Nile Basin Initiative (NBI) is an intergovernmental partnership of 10 riparian states of the Nile River that seeks to develop the Nile River in a co-operative manner so as to share the socio-economic benefits that occur from the development of these transboundary water resources (NBI, 2013). After an extensive consultation process, the NBI developed a wetland management strategy (NBI, 2013) in which it defines wetlands as "*those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support a prevalence of vegetation typically adapted for life in saturated soil conditions*". This definition of a wetland includes swamps, flood plains, seasonally flooded grasslands, the edges and shallow waters of rivers and lakes, estuaries and coastal marshes and mangroves and peat bogs. The strategy also addressed the issue of wetland water catchments that are located in different countries and how upstream hydrological and hydrodynamic changes may have a strong transboundary impact downstream. An integrated and cooperative approached is therefore required to manage and protect the Nile wetlands and to sustain basin-wide benefits, maintain the integrity of these valuable ecosystems, and retain the high levels of functions and services that they perform. The main goal of the wetland management strategy is to foster the sustainable management and utilization of the Nile Basin's wetlands by applying the following principles:

- Wetlands as ecotones which are transitional ecosystems between terrestrial and aquatic systems. The management of the Nile Wetlands need to take into consideration the transitional nature of wetlands to sustain their function and benefits for sustainable development.
- Wise use principle through the implementation of the ecosystem approach in which the ecosystem's benefits and services are maintained to conserve biodiversity and ensure human well-being in the future.
- Equitable wetland resource use through the implementation of rules and regulations to ensure that wetlands users consider the potential impacts on other users and the ecosystem.

The strategic objectives for the Wetland Management Strategy are provided in Table 1

Table 1: Strategic Objectives for the Water Management Strategy (NBI, 2013)

Objective	Description
Objective 1	Strengthen the knowledge base on wetlands of transboundary importance in the Nile Basin to support basin-wide conservation, management, planning and restoration efforts.
Objective 2	Raise awareness and undertake advocacy efforts to build consciousness around the important role of wetlands and their ecosystem functions for the basin's development
Objective 3	Develop and promote a basin-wide approach for the sustainable and cooperative management of wetlands taking into account the full variety of wetland uses.
Objective 4	Strengthen national policies and institutional capacities for the effective management of wetlands with basin-wide importance
Objective 5	Strengthen basin-wide access to finance for wetland management and the capacity for development of feasible projects in the Nile Basin.

Taking all of this into consideration a potential vision for the Nile Basin's wetlands can be summarised as "Fostering the sustainable management and utilization of the Nile Basin's wetlands through the equitable use of wetland resources whilst maintaining the ecosystems' benefits and services." The Sudd wetland itself supports a great biodiversity and provides ecosystem services like food, freshwater, building materials, grazing, navigation and medicinal products as well as various regulating services (NBI, 2016b) and the social and ecological endpoints were selected based on how changes to the e-flows will affect the biodiversity and ecosystem services.

The Sudd wetland is of great socio-ecological importance to the residents of the wetland and the upstream and downstream beneficiaries of ecosystem services provided by the Sudd. This includes but is not limited to the regulatory services of the wetland and provisioning services where the highly productive wetland provides local and regional residents of the Nile basin with fish and other products from the wetland. This process of e-flow determination has been produced using social and ecological information from the other reports to demonstrate the application of and e-flow determination approach which has been undertaken in the Sudd wetland as a part of NBI's efforts to support South Sudan in the process of establishing the necessary knowledge/baseline information sustainable resource management. To this end in this case study the strategic objectives for the Water Management Strategy (NBI, 2013) have been implemented in this demonstration of e-flows determination for the wetland. The endpoints selected to represent this vision is detailed in the next section.

2.2 Endpoints

The social and ecological endpoints that have been defined for the study (Table 2) have been selected based on the ecosystem services that are at risk due to change in the e-flows to the Sudd wetland system and can be used as management goals (USEPA, 2003). Five social endpoints were selected that consider the risk to communities' livelihoods as a result from changes to the ecosystem due to changes in e-flows and 4 ecological endpoints. The ecological endpoints represented different components of the ecosystem that need to be maintained to sustain a functioning ecosystem that will ultimately also affect the livelihoods of local communities.

Table 2: Social and ecological endpoints for the Sudd wetland to foster the sustainable management and utilization of the wetland

Endpoint	Description
Social Endpoints	
Vegetation harvesting for subsistence	Maintain vegetation to sustain community livelihoods through the provision of building materials, firewood and medicinal products.
Subsistence fishing	Maintain fisheries production for community livelihoods.
Water disease	Maintain water levels to ensure that there is no increased risk of water borne disease to local communities.
Grazing	Maintain grasslands for grazing for both livestock and wildlife that are used for subsistence hunting.
Navigation	Maintain waterways for transportation and navigation.
Ecological Endpoints	
Floodplain vegetation	Maintain habitats and ecosystem processes for indicator floodplain macrophytes.
Birds	Maintain habitats and ecosystem processes for indicator resident and migratory birds
Fish	Maintain habitats and ecosystem processes for indicator fishes.
Aquatic invertebrates	Maintain habitats and ecosystem processes for indicator invertebrates

2.3 Data analysis

All available data was to understand the relationship between the social and ecological endpoints of the study. In particular the identification of different habitats within the different wetlands, including: open water, papyrus, reedbeds, flooded grasslands, shrubland, swamp, mudflats, seepage wetlands and woodlands and their characteristics and associated ecosystem processes and ecosystem services have been selected as foundational data for this assessment.

From NBI, 2019a we can summarise the knowledge of the biodiversity and important ecosystem processes of the Sudd that is important for the study as follows:

The Sudd is a maze of wetland ecosystems, grading from open water and submerged vegetation to floating fringe vegetation, seasonally inundated woodlands, rain-fed and river-fed grasslands, and floodplain scrubland (NBI, 2019a). There are three swamp types: *Vossia cuspidata* swamps (which cover 250 km²), *Cyperus papyrus* swamps (3,900 km²) and *Typha domingensis* swamps (13,600 km²). Grassland can be divided into seasonally river-flooded grassland (16,200 km²) and seasonally rain-flooded grassland (20,000 km²). There are areas of single-species woodland mainly of *Acacia seyal* (5,400 km²) or *Balanites aegyptiaca* (5,300 km²). Mixed woodland is characterized by *Ziziphus mauritiana*, *Combretum fragrans*, *Acacia seyal* and *Balanites aegyptiaca* (NBI, 2019a). In the permanent swamps, the channels have a band of Vossia, backed by *Cyperus papyrus*, usually forming a floating mat, which is backed by *Typhia domingensis*. Since 1950, *Eichhornia crassipes* has started to replace *Pistia stratiotes*, the Nile Cabbage. The native free-floating water cabbage has been pushed out and had become confined to temporary pools and small khors.

The Sudd supports high levels of biodiversity and several endangered animal species are found including, *Acinonyx jubatus* (cheetah), *Addax nasomaculatus* (White addax), *Equus grevyi* (Grévy's zebra), various gazelles (*Gazella* dama, *G. dorcas, G. leptoceros, G. rufifrons, G. soemmerringii*), *Kobus megaceros* (Nile lechwe), and *Lycaon pictus* (African wild dog). Other swamp dwelling mammals include Hippopotamus *Amphibius hippoptamus*, *Tragelaphus spekeii* (Sitatunga), *Atilax paludinosus* (Marsh Mongoose). *Kobus megaceros* (Nile Lechwe) is endemic to the Sudd and its movements are related to the flood cycle. It does not live in the swamp but follows the waterline of the river flooded grasslands. *Kobus kob leucotis* (White-eared Kob) make large migrations in the seasonal grasslands, they feed in the grasslands mainly on *Hyparrhenia* and associated grasses. *Loxodonta africana (*elephant) make local movements in the wetlands as the water recedes and giraffes have been seen wading in the water. Migratory mammals depend on the wetland for their dry season grazing. Located on the eastern flyway between Africa and Europe/Asia, the Sudd is one of the most important wintering grounds in Africa for Palaearctic migrants, providing essential habitats for millions of migrating birds such as *Pelecanus onocrotalus* (great white pelican), *Balearica pavonina* (black crowned crane), *Ciconia ciconia* (white stork) and *Chlidonias nigra*. *Balaeniceps rex* (Shoebill) is considered as an icon of the Sudd. The Shoebill avoids the main channels of the swamp and very tall vegetation. The Shoebill prefers the smaller channels and pools specifically those surrounded by Typha. It mostly eats air-breathing fish which the Shoebill ambushes when they come up for air.

Hydrologically the Sudd wetland is regarded as a giant filter that controls and normalizes water quality and a giant sponge that stabilizes water flow. It is the major source of water for domestic, livestock and wildlife use, and an important source of fish. The people living within and adjacent to the Sudd region are almost exclusively Dinka, Nuer and Shilluk. The socio-economic and cultural activities of these Nilotes are entirely dependent on the Sudd wetland and on its annual floods and rains to regenerate floodplain grasses to feed their cattle. They move from their permanent settlements on the highlands to dry season grazing in the intermediate lands (toich) at the beginning of the dry season and return to the highlands in May-June when the rainy season starts.

The Sudd provides a wealth of plants for local residents:

- *Cyperus papyrus* - Local inhabitants cut the tall stems for use as mats and roofing material. Animals graze on its umbels.
- *Phragmites karika* - Culms are used as building material and in mat making.
- *Phragmites sp*. and *Typha sp.* - Major components in phytoremediation, to purify oil contaminated water.
- *Azolla nilotica* - Usually hosts the blue-green, N-fixing *Anabaena azolli*; a small filamentous phototrophic cyanobacteria that provides nitrogen to the *Azolla nilotica*
- *Borassus aethiopium* - Fishing boats are made from the tree timber. Fruits are edible.
- *Hyphaene thebaica* - Trunks are used as building material. Fruits are edible.
- *Eichhornia crassipes* - Grazed by animals, used as mulch and fertilizer and for the generation of biogas.
- *Trapa natans* - The fruit is rich in starch and fat. Used as food.
- Nymphaea spp. - Rhizomes and fruits are used as food by Nilotic tribes.
- *Aeschynomene indica* - Raft making.
- Oryza spp. - Potential rice crop. (Osman, 2009).

The permanent and seasonal aquatic systems of the Sudd wetland play important roles in the life-cycles of many fish species found in the Sudd. The different habitat types ranging from open water, riverine, lacustrine to palustrine provide for the complete life cycle of the fish (Ramsar). Important fish species from the seasonal floodplain habitat are facultative air breathers e.g. *Protopterus aethiopicus, Polypterus senegalus, Heterotis niloticus, Xenomystis nigri, Clarias gariepinus, Ctenopoma muriei,* and Parachan*na obscura*. The important species in the lakes and channels of the perennial wetland are *Synodontis schall*, *S. frontosus* and *Auchenoglanis biscutatis, Alestes dentex* and *Heterotis niloticus*. The Sudd swamps produced about 30,000 t of fish in 2003 (FAO, 2020, Witte et al., 2009). The potential yield of this wetland with a surface of 30,000–40,000 km2 has been estimated at 75,000 t y−1. The prevailing fishing techniques are hook and line, long lines, gill nets, seine nets, cast nets, traps, and spear fishing. However the mesh size of the monofilament gill nets are becoming smaller and the twine thinner (Witte et al., 2009).

The Sudd provides many ecosystem services and has a profound effect on water quality, nutrient retention, and river hydrology. In addition it provides extensive economic and environmental benefits to the entire region; the socioeconomic benefits of the wetland to the communities living in its catchment are immense. It is estimated that over one million people are almost entirely dependent on the wetland, their way of life inextricably tied to the seasonal expanding and shrinking of the swamps and the changing depth of water. The channels of the wetland are used for navigation by both commercial and public steamers as well as boats and canoes. The wetland is a major source of water for domestic use and provides building materials for the local communities. An important source of fish, it is one of the only water bodies of the Nile which is not currently overfished. Due to the lack of processing and storage facilities, commercial fisheries are yet to be exploited.

The Sudd provides a source of water and essential dry-season grazing land for livestock, the backbone of the Nilotes' economy. Most of the tribes living within the Sudd catchment are nomadic and move with their large herds of cattle in response to the annual regime of the Bahr el Jebel and rainfall. Fishing is the second most important occupation of the inhabitants of the wetlands especially the Shilluk and Nuer. Subsistence hunting is also important to the Nilotes of the Sudd catchment. Crop production is not a significant occupation although some subsistence agriculture is carried out in the highland areas during the wet season. The agricultural potential of the area is limited by the vagaries of the climate, pests, weeds, and diseases.

The Sudd has very high cultural values for the Dinka, Nuer, and Shilluk communities. During periods of low flow, the wetland is a social centre for the initiation of relationships and dancing leading to courtship and marriage. The wetland sustains the livestock used as dowries for marriages, religious rituals, and payment of penalties. In addition, the wetland contains various wildlife species considered to be sacred by the Nilotes. These include the Nile lechwe, Shoebill, and the crowned crane (NBI, 2019a).

Threats to the site include oil exploration – Sudd contains south Sudan's largest oil block – and the Jonglei Canal Project, which is currently on hold, but would reduce wet and dry season flows by 20 and 10% respectively, thus impacting the wetland's ecology and consequently its inhabitants. (Ramsar)

2.4 Sources and stressors

The stressors taken into consideration are those that will affect the volume, timing, duration and frequency of flow to the Sudd wetland. These could include proposed potential hydropower sites like the Fula Dam in Nimule and the Bedden Dam in south Juba and the completion of the Jonglei Canal (NBI, 2016b). These pose a risk to the water flow regime that will negatively impact downstream ecosystems and water resource users.

The scenarios (SC) that were considered during the risk assessment were therefore based on statistics used to cover the full range of hydrological percentiles in an approximately even distribution. The hydrodynamic model was run for the period 1 March 1960 to 28 February 1962 to determine the baseline (SC0) with 4 additional scenarios generated by scaling flow and precipitation with the factors given in Table 3 below. This led to 10 different years (2 baseline, 8 scenario) which are analysed individually. To assess the likelihood of the occurrence of the individual years, flows were compared to the full available time series (1950-2014) and percentiles as well as absolute flow values were provided.

Table 3: The list of scenarios and the factor precipitation and flow used in the hydrological model

Scenario	Factor Precipitation	Factor flow
Scenario 0 (SC0) -Baseline	1	1
Scenario 1 (SC1)	0.3	0.3
Scenario 2 (SC2)	0.6	0.6
Scenario 3 (SC3)	1.5	1.5
Scenario 4 (SC4)	2	2
Scenario 5 (SC5)	1.05	1.05
Scenario 6 (SC6)	1.15	1.15
Scenario 7 (SC7)	1.33	1.33

2.5 Risk regions

The study area is delineated spatially and geographically into risk regions or risk zones so that each RR can be assessed in a relative manner (O'Brien et al 2018). Risk regions are generally selected based on a combination of management objectives, source information and habitat data and for this study the Sudd wetland was divided spatial onto three geographical risk regions (Figure 1) based on the hydrodynamics of the area. Risk region 1 (RR1) constitutes the upstream area from where the Bahr el Jebel enters the wetland to where it splits into the Bahr el Jebel and the Bahr el Zefar. The Bahr el Jebel split forms RR2 till the end of the wetland and the Bahr el Zefar split forms RR3. The results of the risk assessment are provided only for RR1 as the in-flows into the wetland in this risk region will determine the flows throughout the wetland and is considered to be the most important risk region to focus on.

2.6 Conceptual model

The original conceptual model (Figure 3) considered the effects of depth, velocity. timing and duration of flows to predict the availability of the different habitats available in the Sudd wetland but it was determined that there is no linear / logarithmic relationship between the flow and the habitat availability so this approach could not be used. Different equations from the hydrodynamic model based on the depth of the water (as explained in Section 2.7) were then used to determine the relationship between discharge and habitat availability based on the controls of the wetland. The green parent exposure nodes of the initial conceptual model were removed and replaced by the predicted available habitats as well as seasonality. The habitats exposure child nodes were reduced to habitats for fish, invertebrates and migrating birds but the endpoint and effects nodes remained the same (Figure 4).

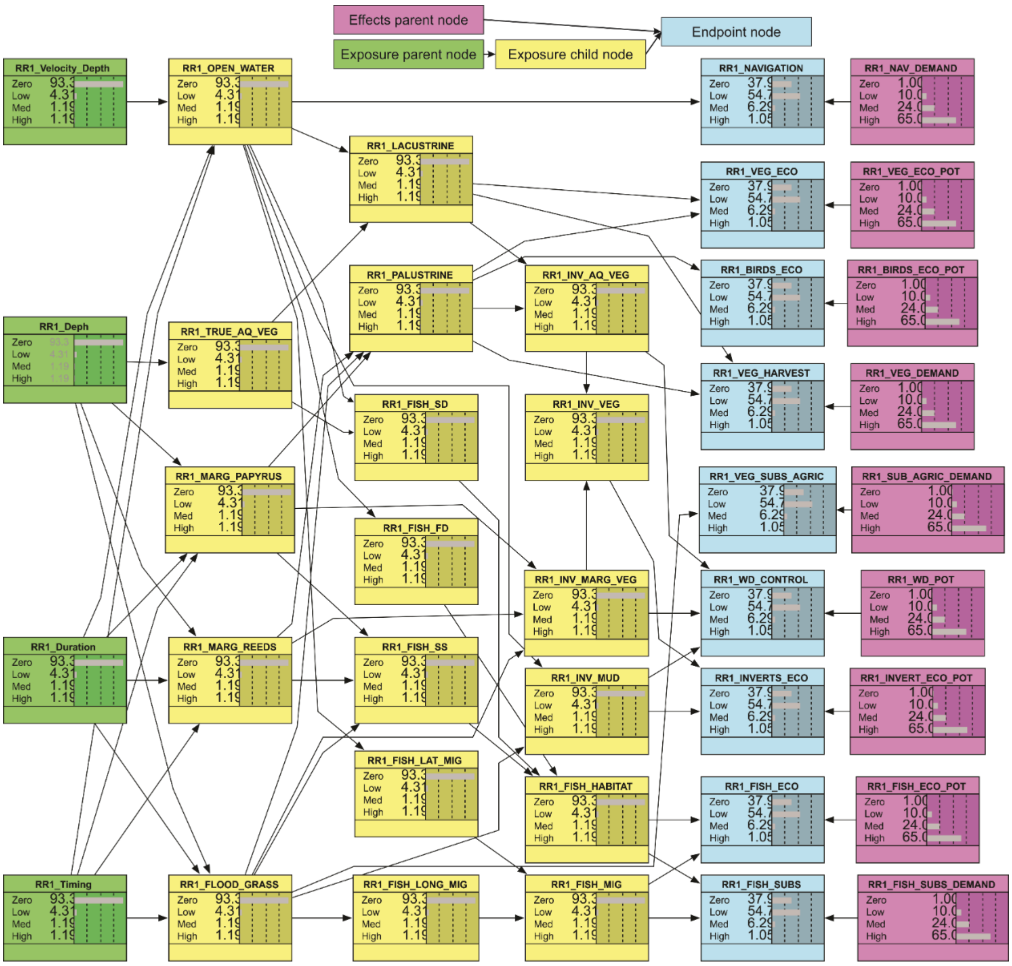

Figure 3: Initial conception model of the risk assessment with the green expose node representing the sources, the pink effects nodes the stressors, the yellow exposure child nodes as the habitats and the blue endpoint nodes.

2.7 Ranking scheme

A ranking scheme is used to represent the state of variables and to facilitate the calculation of risk to the social and ecological endpoints identified in Table 2. Four states namely; zero, low, moderate and high are commonly used for RRM (Colnar and Landis, 2007; Hines and Landis, 2014; Landis et al., 2017a; O'Brien and Wepener, 2012; Wade et al., 2021) and have also been included in the PROBFLO process (O'Brien et al 2018). The ranks were also assigned relative risk scores for the BN and Monte Carlo randomisation evaluations (O'Brien et al 2018). The scores, range of conditions, level of impact and management ideals for each state are provided in Table 4.

Table 4: Ranking scheme states, range of conditions, levels of impact and management ideals (O'Brien et al 2018).

State (model rank score*)	Range of condition	Level of impact	Management ideals
Zero (0-0.25)	Pristine state	No impact or risk	Baseline or reference state
Low (0.26-0.5)	Largely natural state	Low impact or risk	Ideal range for sustainable ecosystem use
Moderate (0.51-0.75)	Moderately modified state	Moderate impact or risk	Representing threshold of potential concern
High (0.76-1)	Significantly altered state	Unacceptably high impact or risk	Failure threshold

Note: (*) refers to the model score assigned to the ranking scheme for inclusion into the Bayesian Network.

2.8 Bayesian networks

Bayesian networks is a graphical modelling tool that represents a system as a network, with all cause-effect assumptions made explicit (Chen and Pollino, 2012). The variables of the BN are represented by nodes that are linked by arcs representing the dependant relationships between variables. Conditional Probability Tables (CPTs) attached to each node define the strength of the relationships between nodes. The CPTs indicate the probability that a node will be in a specific state based on the state of the nodes that directly affect the node (Chen and Pollino, 2012). The Netica^{TM} BN software by Norsys Software (http://www.norsys.com/) was used in this study to create the BN provided in Figure 4, to determine the risk to the endpoints (blue nodes) based on the various flow scenarios provided in Table 3.

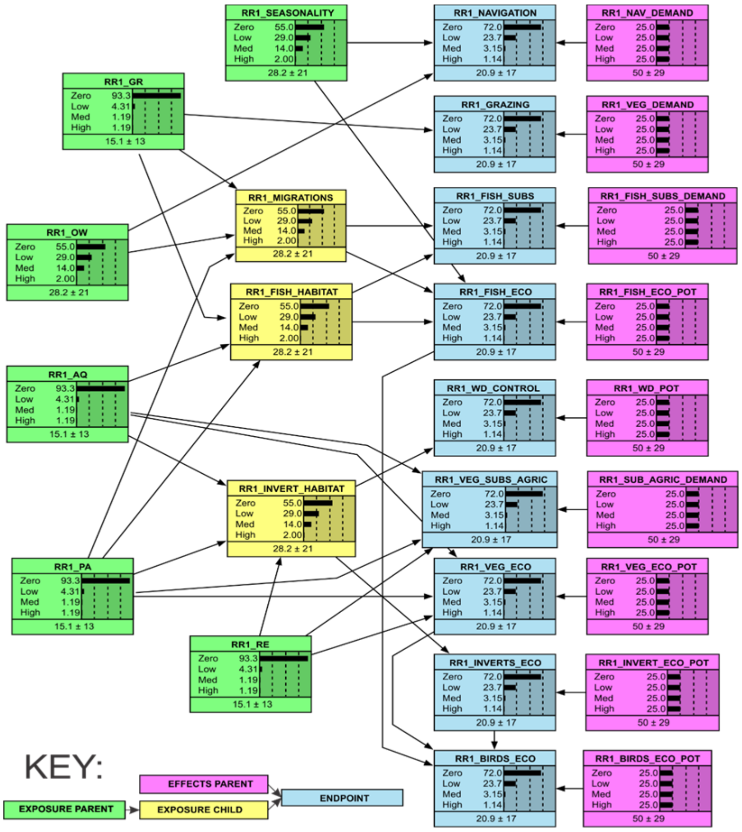

Figure 4: Bayesian network model for the Sudd wetland risk assessment representing casual linkages between the socioecological system variables and the endpoints for the study. The model includes the green input or parent exposure variables, the yellow daughter exposure variables, the pink effects variables and the blue endpoint variables.

ABRV	Meaning
RR1	Risk Region 1
OW	Open water
AQ	Aquatic vegetation
PA	Papyrus
RE	Reed beds
GR	Flooded grassland
INVERT	Invertebrate
VEG	Vegetation
ECO	Ecosystem
SUBS	Subsistence
NAV	Navigation
WD	Water disease
AGRIC	Agriculture
POT	Potential

The data used to input the BN includes data to describe the present condition/state of the range of input variables (exposure parent nodes and effects parent nodes). The condition of these variables is represented using the ranking scheme established for the study and the justification for input (parent nodes) in the study presented in Table 5.

Table 5: Justification for the input parent data into the Bayesian Networks.

Network: variable title (BN node name)	**Rank (score)**	**Rank definition and measure for variable**	**Justification**	**References**
Justification for parent exposure nodes used to determine e-flows in Risk Region 1 (RR1) for the Sudd Wetland				
Deep Open Water, non-vegetated habitats (OW)	Zero (25)	Ideal abundance and or quality of OW habitats that maintains biodiversity, ecosystem processes and ecosystem services in a pristine/near natural state.	Permanently flooded and slow flowing, this ecotype is dominated by free-floating plants like *Eichhornia crassipes*, *Lemna gibba*, *Azolla nilotica* and *Nymphaea lotus* as well as submerged vegetation e.g. Potamogeton, Trapa and Ceratophyllum spp in both slow flowing waters and lakes. Open water habitats provide numerous aquatic animals and plants with habitats. This habitat is important for the maintenance of the biodiversity of the Sudd and promotes important ecosystem processes including the migrations of many fishes. Additional ecosystem services including navigation is also derived from and or dependent on this habitat.	NBI, 2019a
	Low (50)	Suitable abundance and or quality of OW habitats that maintains all biodiversity, ecosystem processes and ecosystem services.		
	Moderate (75)	Sustainability threshold of OW habitats due to moderate change in the abundance and or quality of OW habitats that still maintains all biodiversity, ecosystem processes and ecosystem services.		
	High (100)	Significant decline in abundance and or quality of OW habitats that results in loss of biodiversity, ecosystem processes and ecosystem services exceeding sustainability.		
Open Water Aquatic Vegetation (AQ)	Zero (25)	Ideal abundance and or quality of AQ habitats that maintains biodiversity, ecosystem processes and ecosystem services in a pristine/near natural state.	Permanently flooded and slow flowing, this ecotype is dominated by free-floating plants like Eichhornia crassipes, Lemna gibba, Azolla nilotica and Nymphaea lotus as well as submerged vegetation e.g. Potamogeton, Trapa and Ceratophyllum spp in both slow flowing waters and lakes.	NBI, 2019a
	Low (50)	Suitable abundance and or quality of AQ habitats that maintains all biodiversity, ecosystem processes and ecosystem services.		
	Moderate (75)	Sustainability threshold of AQ habitats due to moderate change in the abundance and or quality of AQ habitats that still maintains all biodiversity, ecosystem processes and ecosystem services.		
	High (100)	Significant decline in abundance and or quality of AQ habitats that results in loss of biodiversity, ecosystem processes and ecosystem services exceeding sustainability.		
Papyrus Marsh (PA)	Zero (25)	Ideal abundance and or quality of PA habitats that maintains biodiversity, ecosystem processes and ecosystem services in a pristine/near natural state.	Permanently flooded and slow flowing but occurs on land that is flooded throughout the year. Dominated along the banks of the river by massive stands of Cyperus papyrus, Vossia cuspidata, Typha domingensis. Associates of the Cyperus swamp are climbers and ferns. Fringe Vegetation characterised by bands of Vossia cuspidata or Echinochloa stagnina, usually followed by Papyrus (Cyperus papyrus).	NBI, 2019a
	Low (50)	Suitable abundance and or quality of PA habitats that maintains all biodiversity, ecosystem processes and ecosystem services.		
	Moderate (75)	Sustainability threshold of PA habitats due to moderate change in the abundance and or quality of PA habitats that still maintains all biodiversity, ecosystem processes and ecosystem services.		
	High (100)	Significant decline in abundance and or quality of PA habitats that results in loss of biodiversity, ecosystem processes and ecosystem services exceeding sustainability.		

Reed beds of Phragmites spp. (RE)	Zero (25)	Ideal abundance and or quality of RE habitats that maintains biodiversity, ecosystem processes and ecosystem services in a pristine/near natural state.	A permanently and seasonally flooded zone where the main, shallow flooded species, Phragmites australis, Echinochloa pyramidalis, and Oryza barthii are limited to sites where the maximum depth of flooding does not exceed 130 cm.	NBI, 2019a
	Low (50)	Suitable abundance and or quality of RE habitats that maintains all biodiversity, ecosystem processes and ecosystem services.		
	Moderate (75)	Sustainability threshold of RE habitats due to moderate change in the abundance and or quality of RE habitats that still maintains all biodiversity, ecosystem processes and ecosystem services.		
	High (100)	Significant decline in abundance and or quality of RE habitats that results in loss of biodiversity, ecosystem processes and ecosystem services exceeding sustainability.		
River flooded Grassland (GR)	Zero (25)	Ideal abundance and or quality of GR habitats that maintains biodiversity, ecosystem processes and ecosystem services in a pristine/near natural state.	Seasonally flooded for about 90 days in the wet season. These grasslands are seasonally flooded to varying extent and depth by the river. During the rainy season the plains of this belt are often swampy and completely covered with luxuriant growth of tall grasses. Species composition and biomass is closely linked to soil type and degree of inundation. The tall grasses are dominated by Phragmites, Sorghum, Hyparrhenia and Setaria spp as well as Oryza and Echinochloa. Two grassland types are recognized. These are wild rice grassland dominated by Oryza longistaminata and Echinochloa grassland dominated by Echinochloa pyramidalis. Sedges, herbs and other grasses such as Sporobolus pyramidalis associate with the Oryza grassland. It is the most productive grassland type in terms of year-round grazing for livestock and wildlife because of the high protein content of dead materials of wild rice grass. The Echinochloa grassland associates with Oryza and legumes like Desmodium hirtum.	NBI, 2019a
	Low (50)	Suitable abundance and or quality of GR habitats that maintains all biodiversity, ecosystem processes and ecosystem services.		
	Moderate (75)	Sustainability threshold of GR habitats due to moderate change in the abundance and or quality of GR habitats that still maintains all biodiversity, ecosystem processes and ecosystem services.		
	High (100)	Significant decline in abundance and or quality of GR habitats that results in loss of biodiversity, ecosystem processes and ecosystem services exceeding sustainability.		
Seasonal flow variability (SEASONALITY)	Zero (25)	Seasonality of flows in the wetland and associated provision of habitats maintain ideal condition of seasonality dependent biodiversity and ecosystem processes.	The Sudd has a profound effect on river hydrology. Communities are almost entirely dependent on the seasonal expanding and shrinking of the swamps and the changing depth of water. Habitat types of the Sudd included permanently and seasonally flooded zones with varying depths. Ideal habitat depths range from 0.5 - 1.5m across the habitat types. Biological cues are triggered by flood timing which is critical to ensure that ecosystem functions and use and sustainability are protected. The more natural the timing of floods the lower the risk to the resource due to its timing or mis-timing. Flood duration is important to productivity and reproduction (plants and fish), shorter periods will result in reduced	NBI, 2019a
	Low (50)	Suitable condition of flows in the wetland and associated provision of habitats maintain seasonality dependent biodiversity and ecosystem processes.		
	Moderate (75)	Sustainability threshold of seasonal flow variability into the wetland that maintains all biodiversity and ecosystem processes.		
	High (100)	Significant change in the seasonality of flows into the wetland resulting in unsustainable conditions for seasonality dependent animals and ecosystem processes in the wetland.		

			productivity, failure of reproduction. The shrinkage of floodplains is also important for species migration between areas that follow changing water levels and vegetation.	
Ecological importance of vegetation (VEG_ECO_POT)	Zero (25)	Importance of the vegetation in the wetland is insignificant and will not contribute to the determination of the ecological consequences of altered flows in the study.	The Sudd is composed of a maze of wetland ecosystems, grading from open water and submerged vegetation to floating fringe vegetation, seasonally inundated woodlands, rain-fed and river-fed grasslands, and floodplain scrubland. Measure is based on depth distribution for habitat units, optimal ranges include Open water > 1.3m (rooted species only), papyrus marsh flooding below 1.5m, reeds 0.5-1.3m, swamps 0.5 - 2m with gentle seasonal fluctuations, mud flats shallow	NBI, 2019a
	Low (50)	Small value of vegetation as an ecological indictor in the determination of the ecological consequences of altered flows in the study.		
	Moderate (75)	Vegetation is an important ecological indicator that should drive the determination of the ecological consequences of altered flows in the study.		
	High (100)	Vegetation is a critical ecological indicator that drives the determination of the ecological consequences of altered flows in the study.		
Demand for Grazing (GRZ_DEMAND)	Zero (25)	Importance of the grazing in the wetland is insignificant and will not contribute to the determination of the social consequences of altered flows in the study.	The Sudd provides a source of water and essential dry-season grazing land for livestock, the backbone of the Nilotes' economy. Most of the tribes living within the Sudd catchment are nomadic and move with their large herds of cattle in response to the annual regime of the Bahr el Jebel and rainfall. Fishing is the second most important occupation of the inhabitants of the wetlands especially the Shilluk and Nuer. Subsistence hunting is also important to the Nilotes of the Sudd catchment. Crop production is not a significant occupation although some subsistence agriculture is carried out in the highland areas during the wet season. The agricultural potential of the area is limited by the vagaries of the climate, pests, weeds, and diseases (Rebelo & El-Moghraby, 2016). Measure is based on demand. Zero = No demand by communities, Low is seasonal and subsistence demand, Moderate is continuous subsistence demand, High is consistent and commercial demand.	(Rebelo & El-Moghraby 2016)
	Low (50)	Small value of grazing as a social indictor in the determination of the ecological consequences of altered flows in the study.		
	Moderate (75)	Grazing is an important a social indicator that should drive the determination of the social consequences of altered flows in the study.		
	High (100)	Grazing is a critical social indicator that drives the determination of the social consequences of altered flows in the study.		
Ecological importance of fish (FISH_ECO_POT)	Zero (25)	Importance of the fish in the wetland is insignificant and will not contribute to the determination of the ecological consequences of altered flows in the study.	The Sudd contributes provisioning ecosystem services in the form of food (fish, game and fruits). Fishing is also an important seasonal activity and source of food as fish migrate to the nutrient-rich floodplains. Many fish species migrate from the surrounding rivers to the nutrient-rich floodplains to feed and breed during the seasonal floods and therefore play an important role in the life cycles of many fish species identified in the wetland. The different habitat types ranging	NBI, 2021
	Low (50)	Small value of fish as an ecological indictor in the determination of the ecological consequences of altered flows in the study.		
	Moderate (75)	Fish is an important ecological indicator that should drive the determination of the ecological consequences of altered flows in the study.		

	High (100)	Fish is a critical ecological indicator that drives the determination of the ecological consequences of altered flows in the study.	from open water, riverine, lacustrine to palustrine offer ideal conditions for over hundred species of fish. Hydraulic data is available to represent the instream velocity and depth (VD) profile based on discharge (m3/s) which has been selected as the measure for this variable.	
Demand for fisheries (FISH_SUBS_DEMAND)	Zero (25)	Importance of fish for food in the wetland is insignificant and will not contribute to the determination of the social consequences of altered flows in the study.	Fishing is also an important seasonal activity and source of food as fish migrate to the nutrient-rich floodplains. The second most important occupation of the inhabitants is fishing, especially the Shilluk and Nuer. Subsistence hunting is also important to the Nilotes of the Sudd catchment. Measure is the abundances of people per risk region.	NBI 2019a;b; NBI 2021
	Low (50)	Small value of fish as food as a social indictor in the determination of the ecological consequences of altered flows in the study.		
	Moderate (75)	Fisheries is an important a social indicator that should drive the determination of the social consequences of altered flows in the study.		
	High (100)	The fishery of the wetland is a critical social indicator that drives the determination of the social consequences of altered flows in the study.		
Demand for vegetation for subsistence (SUB_AGRIC_DEMAND)	Zero (25)	Importance of harvested plants in the wetland is insignificant and will not contribute to the determination of the social consequences of altered flows in the study.	Subsistence agriculture is conducted in the highland areas during the wet season, but crop production is not regarded as a significant occupation. The agricultural potential of the area is limited by the vagaries of the climate, pests, weeds, and diseases (Rebelo & El-Moghraby, 2016). Measure is the abundances (expected demand) of people per risk region.	NBI, 2019a; Rebelo & El-Moghraby 2016)
	Low (50)	Small value of harvested plants as a social indictor in the determination of the ecological consequences of altered flows in the study.		
	Moderate (75)	Plants harvested in the wetland is an important a social indicator that should drive the determination of the social consequences of altered flows in the study.		
	High (100)	Plants harvested in the wetland is a critical social indicator that drives the determination of the social consequences of altered flows in the study.		
Potential threat of water disease to people (WD_POT)	Zero (25)	Water disease potential is insignificant in the wetland and will not contribute to the determination of the social consequences of altered flows in the study.	Hydrologically the Sudd wetland is regarded as a giant filter that controls and normalizes water quality and a giant sponge that stabilizes water flow. The wetland is a major source of water for domestic use. Communities closer to the system will contribute to water quality impairment. Greater densities are likely to result in greater impairment. Measure is based on the population density figures (people per km2 within 5km buffer) Zero = 0 ppl/km2, Low = 1-35, Mod = 35-50, High >50.	NBI, 2019a
	Low (50)	Potential for water disease is small and will have a small contribution to the determination of the social consequences of altered flows in the study.		
	Moderate (75)	e potential for water disease associated with altered flows is an important a social indicator that should drive the determination of the social consequences of altered flows in the study.		
	High (100)	The threat of water disease in the wetland is a critical social indicator that drives the determination of the social consequences of altered flows in the study.		

Ecological importance of aquatic invertebrates (INVERT_ECO_POT)	Zero (25)	Importance of the invertebrates in the wetland is insignificant and will not contribute to the determination of the ecological consequences of altered flows in the study.	The ecological importance and sensitivity (EIS) is rated "High", with the Sudd providing vast slow water zones and backwaters for invertebrates. Invertebrates have different preferences which include special preference for submerged stones, aquatic vegetation and submerged plant stems and roots as well as sediments. Aquatic and marginal vegetation is an important biotope for invertebrates as a habitat and food source. Highest abundances and diversity are common stones/riffle habitat, followed by vegetation and then GSM/Bedrock. Measure is semi-quantitative description of available biotopes, Zero = natural biotopes available (> 3 biotopes), Low Risk suitable biotopes quality (close to natual) and diversity (> 2 biotopes) available, Moderate loss of biotope availability evident, and degradation of quality (< 2 biotopes available), High risk loss of biotopes and quality of available biotopes poor (< 2 biotopes)	NBI, 2019a
	Low (50)	Small value of invertebrates as an ecological indictor in the determination of the ecological consequences of altered flows in the study.		
	Moderate (75)	Aquatic invertebrates are an important ecological indicator that should drive the determination of the ecological consequences of altered flows in the study.		
	High (100)	Invertebrates is a critical ecological indicator that drives the determination of the ecological consequences of altered flows in the study.		
Ecological importance of migratory and resident birds (BIRDS_ECO_POT)	Zero (25)	Importance of the birds in the wetland is insignificant and will not contribute to the determination of the ecological consequences of altered flows in the study.	Migratory birds depend on the wetland for their dry season grazing. The Sudd provides important habitats for migrating birds, positioned on the eastern flyway between Africa and Europe/Asia. The Suud wetland ranks high because of the total area of the IBA associated with the system. Balaeniceps rex (Shoebill) is considered as an icon of the Sudd and it avoids the main channels of the swamp and very tall vegetation but prefers the smaller channels and pools specifically those surrounded by Typha. The measurement in discharge (m3/s) which is linked to the velocities in the risk region via a calibrated hydrodynamic model.	NBI, 2019a
	Low (50)	Small value of birds as an ecological indictor in the determination of the ecological consequences of altered flows in the study.		
	Moderate (75)	Birds are an important ecological indicator that should drive the determination of the ecological consequences of altered flows in the study.		
	High (100)	Birds are a critical ecological indicator that drives the determination of the ecological consequences of altered flows in the study.		
Demand for navigation (NAV_DEMAND)	Zero (25)	The need for habitats to allow navigation is insignificant in the wetland and will not contribute to the determination of the social consequences of altered flows.	The Sudd wetland is used as well for commercial and non-commercial navigation (Rebelo & El-Moghraby 2016). The channels of the wetland are used for navigation by both commercial and public steamers as well as boats and canoes. Measure is, velocity gradient with a minimum depth of 1m for canoes, Zero risk = <0.1m/s flow velocity , low risk = 0.1-1m/s, moderate, 1-5m/s. High risk >5--10m/s.	(Rebelo & El-Moghraby 2016)
	Low (50)	the need for habitats that allow navigation in the wetland is small and will have a small contribution to the determination of the social consequences of altered flows in the study.		
	Moderate (75)	The potential for water disease associated with altered flows is an important a social indicator that should drive the determination of the social consequences of altered flows in the study.		
	High (100)	The threat of water disease in the wetland is a critical social indicator that drives the determination of the social consequences of altered flows in the study.		

To represent flow (discharge) from the White Nile into the Sudd as a part of this assessment the matrix tool used as part of the Nile Basin decision support system (NBI, 2019a) was used to predict the availability of habitat based on the water depth and duration of flows (Figure 5). This tool considered seasonality as well as depth duration relationships to predict the type of habitats that would occur in a specific wetland area. To determine how much of a specific habitat is required for the wetland to be in an ideal or suitable (reference) state, the data provided in the matrix (Figure 5) was converted into suitable depth range requirements for specific habitats to occur which in turn was converted to determine the relationship between depth and discharge. In this way depth and flow duration preferences were established for all the habitat types. The existence of a specific habitat type could then be predicted if the discharge amount were known.

Depth (max flood)	Inundation Duration (% Year)																			
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
0	TR	TR	TR	TR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	RE	RE	PA
0.25	TR	TR	TR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	RE	RE	RE	RE	RE	RE	PA
0.5	TR	TR	GR	GR	GR	RE	RE	RE	PA	PA	PA	PA	PA	PA	PA	PA	PA	PA	PA	PA
0.75	TR	GR	GR	GR	GR	RE	RE	PA	PA	PA	PA	PA	PA	PA	PA	PA	PA	PA	PA	PA
1	TR	GR	GR	GR	GR	RE	PA	PA	PA	PA	PA	PA	PA	PA	PA	PA	PA	FR	FR	FR
1.25	GR	GR	GR	GR	GR	RE	PA	PA	PA	PA	PA	PA	PA	PA	FR	FR	FR	FR	FR	AQ
1.5	GR	GR	GR	RE	RE	PA	PA	PA	PA	PA	PA	PA	FR	FR	FR	AQ	AQ	AQ	AQ	OW
1.75	GR	GR	GR	PA	PA	PA	PA	PA	PA	PA	FR	FR	AQ	AQ	AQ	AQ	AQ	AQ	OW	OW
2	GR	RE	RE	PA	PA	PA	FR	FR	FR	FR	FR	AQ	AQ	AQ	AQ	AQ	AQ	OW	OW	OW
2.25	GR	RE	RE	PA	PA	FR	FR	FR	AQ	AQ	AQ	AQ	AQ	AQ	AQ	OW	OW	OW	OW	OW
2.5	RE	RE	PA	PA	FR	AQ	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW
2.75	RE	PA	PA	PA	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW
3	RE	PA	PA	PA	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW
Days	18.25	37	55	73	91	110	128	146	164	183	201	219	237	256	274	292	310	329	347	365

Figure 5: Matrix tool (NBI, 2019a) used to predict the habitat availability based on the water depth and duration of flows (OW- open water, AQ – aquatic vegetation, FR – fringe vegetation, PA – papyrus marsh, RE – reedbeds, GR – grassland floodplains, TR – trees and shrubs).

Table 6: Habitat frequencies from the Sudd Wetland associated with depth frequencies derived from NBI, 2019a in Figure 3.

	OW	AQ	FR	PA	RE	GR	TR
0	0	0	0	1	2	13	3
0.25	0	0	0	1	6	10	2
0.5	0	0	0	12	3	3	1
0.75	0	0	0	13	2	4	0
1	0	0	3	11	1	4	0
1.25	0	1	5	8	1	4	0
1.5	1	4	3	7	2	2	0
1.75	2	6	2	7	0	2	0
2	3	6	5	3	2	0	0
2.25	5	7	3	2	2	0	0
2.5	14	1	1	2	1	0	0
2.75	16	0	0	3	0	0	0
3	16	0	0	3	0	0	0

0.1	$y = 4859\ln(x) - 26398$
1	$y = 617.57\ln(x) - 3210.7$
1.5	$y = 369.89\ln(x) - 2246.1$
2	$y = 106.63\ln(x) - 590.79$
2.5	$y = 61.821\ln(x) - 383.2$
3	$y = 17.842\ln(x) - 106.86$
4	$y = 11.265\ln(x) - 63.883$
5	$y = 4.4517\ln(x) - 24.658$

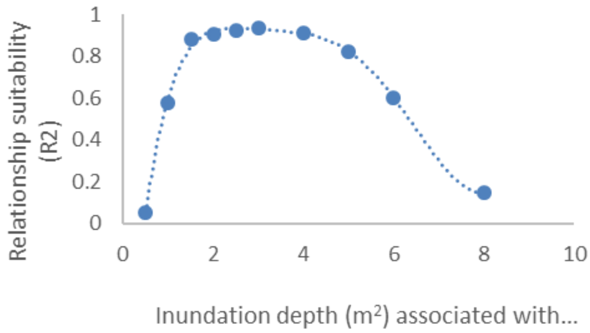

Figure 6: Flow-habitat relationship equations (left) and relationship confidence (right) derived for the Sudd Wetland case study using the Hydrodynamic model generate for the Sudd by Kiesel et al., 2020.

Table 7: Habitat depth and associated discharge specifications for the PROBFLO Bayesian Network evaluation of the risk of altered flows to the Sudd Wetland.

	OW		AQ		FR		PA	
	Low (m)	**high (m)**	**Low (m)**	**high (m)**	**Low (m)**	**high (m)**	**Low (m)**	**high (m)**
ZERO/LOW	2.5		1.75	2.25	1.25	2	0.5	1.25
LOW/MOD	1.75		1.5	2.5	1.5	2.5	0.25	1.75
MOD/HIGH	1.5		1.25	2.75	1	2.75	0	3
	OW		**AQ**		**FR**		**PA**	
	Low (m)	**high (m)**	**Low (m)**	**high (m)**	**Low (m)**	**high (m)**	**Low (m)**	**high (m)**
ZERO/LOW	910		730	850	630	780	520	630
LOW/MOD	730		680	910	680	910	480	730
MOD/HIGH	680		630	980	590	980	400	1050

	RE		GR		TR	
	Low (m)	**high (m)**	**Low (m)**	**high (m)**	**Low (m)**	**high (m)**
ZERO/LOW	0.1	0.25	0.1	0.1	0.05	0.1
LOW/MOD	0	0.5	0	1	0	0.25
MOD/HIGH		1.5		2		0.5
	RE		**GR**		**TR**	
	Low (m)	**high (m)**	**Low (m)**	**high (m)**	**Low (m)**	**high (m)**
ZERO/LOW	425	480	425	425	380	425
LOW/MOD	400	520	400	590	400	480
MOD/HIGH		680		780		590

The scenarios used to populate the input nodes in the risk assessment were obtained from the Coarse e-flow assessment for the Nile Basin, specifically the flow scenarios obtained from Bahr el Jebel flows at Mangala (Figure 7 and Figure 8), and hydrological scenarios considered in the determination of the hydrodynamic model for the Sudd wetland by Kiesel et al., 2020 (Appendices).

The reference flows for the dry phase observed between 1905 and 1960 were used to establish baseline habitat characteristics for the Sudd Wetland (Figure 7A). *These baseline habitat characteristics are considered to be naturally observed flows resulting in modelled habitat distributions used in this study.* All of the alternative hydrology scenarios were evaluated against this baseline habitat characteristics. This allows for the evaluation of the socio-ecological consequences of altered flows associated with changes in the volume, timing and duration of flows into the Sudd Wetland.

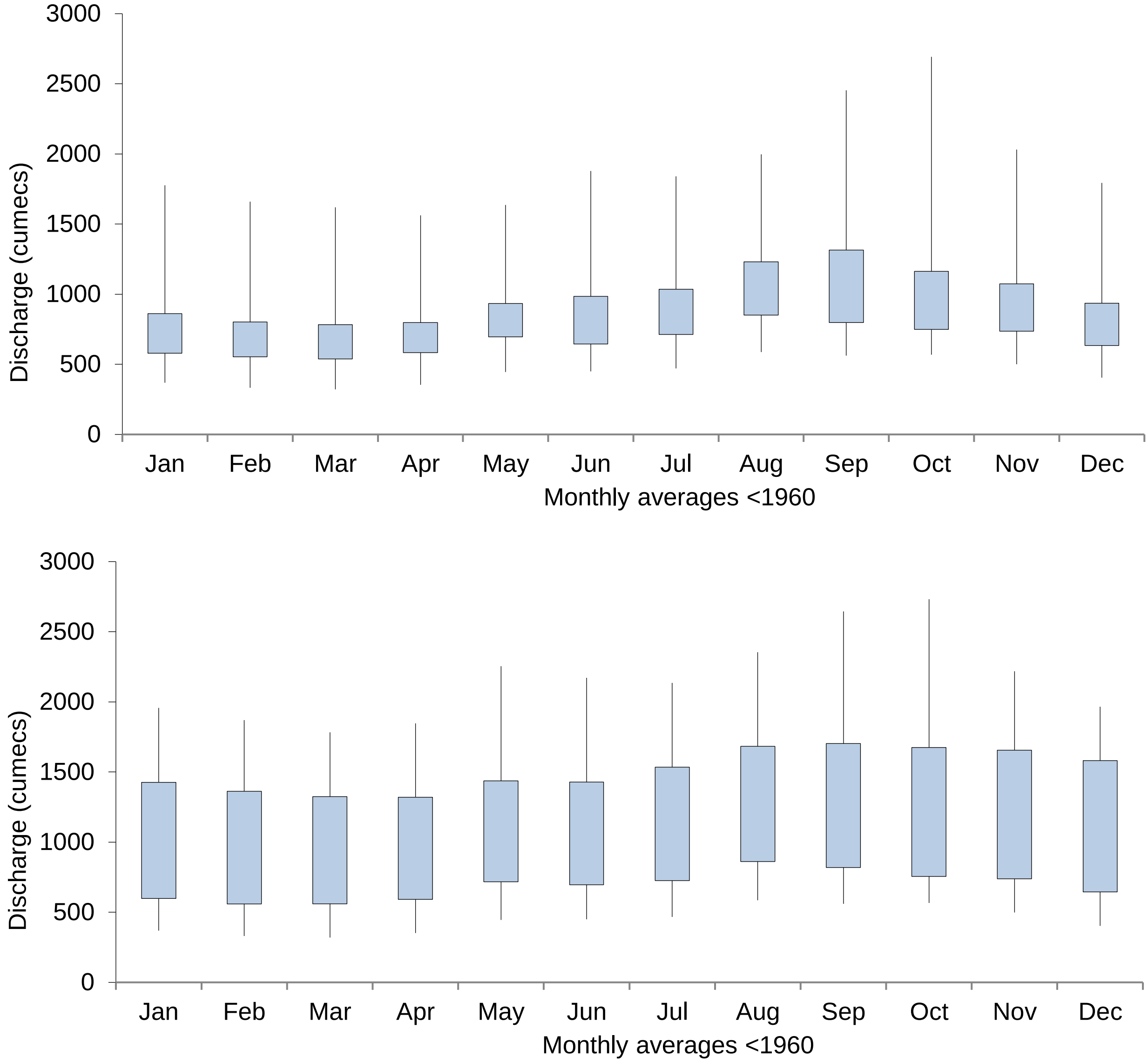

Figure 7: Reference hydrology scenarios (A = 1905-1960, B = 1961 to 1985) considered in the study using box and whisker plots (box 20-80%tiles) and whisker 0.01%tiles and 99.9%tiles.

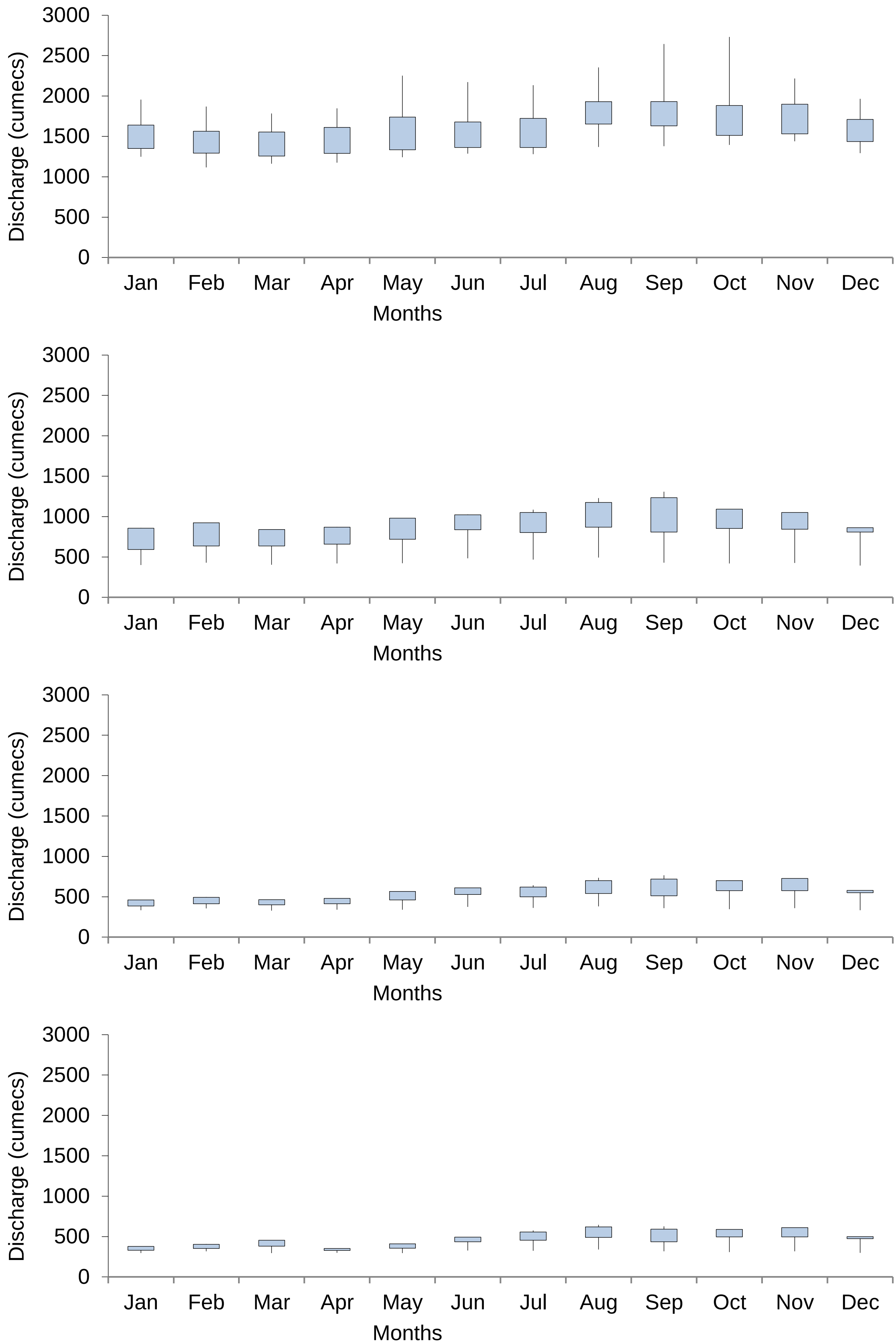

Figure 8: Hydrology scenarios determined in the coarse E-flow assessment for selected sites in the Nile (O'Brien et al., 2019) for the White Nile upstream of the Sudd Wetland. Graphs represent integrated (1905-1985) reference flows associated with Class A (A) and e-flows established to meet Class B (B), Class C (C) and Class D (D).

The child nodes used in the NB represent variables of the socio-ecological system being evaluated that are determined by the interaction of two or more parent nodes, as per the conceptual model and BN (Figure 4).

The interaction of the parent variables is based on rules or conditional probabilities presented in this study as CPTs. The CPTs for all of the exposure child and endpoint nodes were established in the study through evaluation of available data that (a) describes the representation of the variable considered and then (b) we used an equation tool in Netica™ to generate relationship CPTs and then refined them to best represent available knowledge of the socio-ecological system variable. An example includes the use of the equation below (Equation 1) to determine the initial CPT table to represent the interaction of the Seasonality of flows (SEASONALITY node) and the condition of Open Water (OW node) and Grassland habitats (GR node) used by the fish in the Sudd Wetland for Migrations (MIGRATION node).

Importantly this variable considers if each of these parent nodes are available and in what condition and then predicts the potential for fish migrations from OW to GR habitats which in this case study was included as an important component of both the fish as ecological indicators and the availability of fish for food as an ecosystem endpoint in the study. Here we used Equation 1 as a foundational equation to weight the importance of either the SEASONALITY, GR and or OW occurring in a high-risk state (or unsustainable state) that will drive the suitability of the "MIGRATIONS" variable. Here the portion of input or parent nodes observed to be in a "high risk state" would have a 66% weighting resulting in a high-risk distribution for the MIGRATIONS node (Equation 1.1, 1.2 and 1.3). Thereafter any other rank state would have an equal weighting (Equation 1.4, 1.5 and 1.6) to determine the resulting CPT for the variable presented in **Error! Reference source not found.**. Based on limited data availability to describe the interactions of the Seasonality of flows, condition of Open Water and Grassland habitats this CPT was incorporated directly into the BN for the assessment.

Equation 1: Equation used to generate initial CPT for the "MIGRATIONS" node in the study.

1. p(RR1_MIGRATIONS|RR1_SEASONALITY,RR1_GR,RR1_OW)=
2. (RR1_OW>75)?NormalDist(RR1_MIGRATIONS,((RR1_SEASONALITY*0.5)+(RR1_GR*0.5)+(RR1_OW*2))/3,7.5):
3. (RR1_SEASONALITY>75)?NormalDist(RR1_MIGRATIONS,((RR1_SEASONALITY*2.5)+(RR1_GR*0.25)+(RR1_OW*0.25))/3,7.5):
4. (RR1_OW<75)?NormalDist(RR1_MIGRATIONS,((RR1_SEASONALITY*1)+(RR1_GR*1)+(RR1_OW*1))/3,7.5):
5. (RR1_SEASONALITY<75)?NormalDist(RR1_MIGRATIONS,((RR1_SEASONALITY*1)+(RR1_GR*1)+(RR1_OW*1))/3,7.5):
6. (RR1_GR>75)?NormalDist(RR1_MIGRATIONS,((RR1_SEASONALITY*0.5)+(RR1_GR*2)+(RR1_OW*0.5))/3,7.5):
7. NormalDist(RR1_MIGRATIONS,((RR1_SEASONALITY*1)+(RR1_GR*1)+(RR1_OW*1))/3,7.5)

Table 8: Conditional Probability table representing risk distribution assignment for the MIGRATIONS child node in the study as a percentage.

SEASONALITY	GR	OW	Zero	Low	Moderate	High
Zero	Zero	Zero	89.6	8.3	1.1	1.1
Zero	Zero	Low	61.8	36.4	0.9	0.9
Zero	Zero	Moderate	33.8	63.2	1.9	1.1
Zero	Zero	High	1.0	7.1	84.9	7.0
Zero	Low	Zero	62.3	35.9	0.9	0.9
Zero	Low	Low	31.9	65.5	1.6	0.9
Zero	Low	Moderate	5.8	83.1	10.2	0.9
Zero	Low	High	1.0	3.7	73.0	22.4
Zero	Moderate	Zero	33.4	63.4	2.2	1.0
Zero	Moderate	Low	8.5	82.3	8.3	1.0
Zero	Moderate	Moderate	2.1	70.7	26.3	1.0
Zero	Moderate	High	1.0	1.9	67.8	29.3
Zero	High	Zero	9.9	83.2	5.9	1.0
Zero	High	Low	1.5	65.4	32.2	0.9
Zero	High	Moderate	1.0	32.9	64.6	1.6

SEASONALITY	GR	OW	Zero	Low	Moderate	High
Zero	High	High	1.0	1.1	45.6	52.3
Low	Zero	Zero	67.6	30.3	1.1	1.1
Low	Zero	Low	28.1	69.5	1.5	0.9
Low	Zero	Moderate	7.5	82.7	8.9	1.0
Low	Zero	High	0.9	3.5	76.2	19.5
Low	Low	Zero	35.7	61.4	1.9	1.0
Low	Low	Low	8.3	84.9	5.7	1.1
Low	Low	Moderate	1.9	69.7	27.4	1.0
Low	Low	High	0.9	1.4	66.6	31.0
Low	Moderate	Zero	10.0	81.8	7.1	1.0
Low	Moderate	Low	1.4	69.9	27.8	0.9
Low	Moderate	Moderate	1.0	28.5	68.8	1.8
Low	Moderate	High	1.0	1.3	52.6	45.2
Low	High	Zero	1.4	69.7	27.9	1.0
Low	High	Low	0.9	31.5	66.3	1.3
Low	High	Moderate	1.0	6.8	83.5	8.6
Low	High	High	1.0	1.0	27.8	70.2
Moderate	Zero	Zero	32.9	64.9	1.3	0.9
Moderate	Zero	Low	8.5	82.7	7.9	0.9
Moderate	Zero	Moderate	1.8	67.5	29.7	1.0
Moderate	Zero	High	1.0	1.9	64.2	32.9
Moderate	Low	Zero	7.0	84.6	7.4	1.0
Moderate	Low	Low	2.3	70.5	26.1	1.1
Moderate	Low	Moderate	0.9	34.4	63.0	1.7
Moderate	Low	High	0.9	1.1	45.2	52.7
Moderate	Moderate	Zero	1.9	66.4	30.8	0.9
Moderate	Moderate	Low	1.0	31.6	65.5	1.9
Moderate	Moderate	Moderate	1.0	6.6	83.9	8.6
Moderate	Moderate	High	1.0	1.1	32.0	65.8
Moderate	High	Zero	1.1	29.6	67.2	2.2
Moderate	High	Low	1.0	7.9	84.5	6.7
Moderate	High	Moderate	0.9	1.8	64.9	32.4
Moderate	High	High	1.1	1.1	20.6	77.3
High	Zero	Zero	1.0	1.3	55.6	42.1
High	Zero	Low	0.9	1.1	45.0	53.1
High	Zero	Moderate	1.0	1.2	36.8	61.0
High	Zero	High	1.0	1.1	48.4	49.6
High	Low	Zero	1.1	1.3	42.3	55.4
High	Low	Low	1.0	1.1	36.1	61.8
High	Low	Moderate	1.0	1.0	28.9	69.2
High	Low	High	1.0	1.0	33.3	64.7
High	Moderate	Zero	1.0	1.1	30.2	67.7
High	Moderate	Low	1.0	1.0	28.2	69.8
High	Moderate	Moderate	1.0	1.0	19.3	78.7
High	Moderate	High	1.0	1.0	19.0	79.0
High	High	Zero	1.0	1.0	27.6	70.5
High	High	Low	1.0	1.1	17.5	80.4
High	High	Moderate	1.1	1.1	16.1	81.7
High	High	High	1.1	1.1	7.6	90.3

The endpoint nodes were all adjusted following the use of baseline equations in the BN assessment to represent the socio-ecological response part of the regional scale ecological risk assessment framework considered in the study. Here the flexibility of the BN approach is clearly demonstrated where for all social endpoints considered in the study we included the requirement associated with the ranking scheme that only when the demand for an ecosystem service associated end-point is in a moderate or high risk state representing the dependence of the community on the endpoint only then the potential threats to the endpoint would be considered. Thus, the standard equations used in the study resulting in a CPT were radically modified to represent this knowledge of the endpoint.

Equation 2: Equation used to generate initial CPT for the “SUBSISTENCE FISHERIES” node in the study.

1. p(RR1_FISH_SUBS|RR1_FISH_SUBS_DEMAND,RR1_MIGRATIONS,RR1_FISH_HABITAT)=
2. (RR1_FISH_HABITAT>75)?NormalDist(RR1_FISH_SUBS,((RR1_FISH_SUBS_DEMAND*0.5)+(RR1_MIGRATIONS*0.5)+(RR1_FISH_HABITAT*2))/3,7.5):
3. (RR1_FISH_SUBS_DEMAND>75)?NormalDist(RR1_FISH_SUBS,((RR1_FISH_SUBS_DEMAND*1)+(RR1_MIGRATIONS*1)+(RR1_FISH_HABITAT*1))/3,7.5):
4. (RR1_FISH_HABITAT<75)?NormalDist(RR1_FISH_SUBS,((RR1_FISH_SUBS_DEMAND*1)+(RR1_MIGRATIONS*1)+(RR1_FISH_HABITAT*1))/3,7.5):
5. (RR1_FISH_SUBS_DEMAND<75)?NormalDist(RR1_FISH_SUBS,((RR1_FISH_SUBS_DEMAND*1)+(RR1_MIGRATIONS*1)+(RR1_FISH_HABITAT*1))/3,7.5):
6. (RR1_MIGRATIONS>75)?NormalDist(RR1_FISH_SUBS,((RR1_FISH_SUBS_DEMAND*0.5)+(RR1_MIGRATIONS*2)+(RR1_FISH_HABITAT*0.5))/3,7.5):
7. NormalDist(RR1_FISH_SUBS,((RR1_FISH_SUBS_DEMAND*1)+(RR1_MIGRATIONS*1)+(RR1_FISH_HABITAT*1))/3,7.5)

Table 9: Conditional Probability table for the Subsistence fishery (FISH_SUBS) endpoint used in the study including equation derived CPT and Adjustments based on available data.

FISH_SUBS _DEMAND	MIGRA-TIONS	FISH_ HABITAT	Equation derived CPT				Adjustments based on data			
			Zero	Low	Moderate	High	Zero	Low	Moderate	High
Zero	Zero	Zero	89.6	8.3	1.1	1.1	89.0	8.9	1.0	1.0
Zero	Zero	Low	61.8	36.4	0.9	0.9	89.0	8.9	1.0	1.0
Zero	Zero	Moderate	33.8	63.2	1.9	1.1	89.0	8.9	1.0	1.0
Zero	Zero	High	1.0	7.1	84.9	7.0	89.0	8.9	1.0	1.0
Zero	Low	Zero	62.3	35.9	0.9	0.9	89.0	8.9	1.0	1.0
Zero	Low	Low	31.9	65.5	1.6	0.9	89.0	8.9	1.0	1.0
Zero	Low	Moderate	5.8	83.1	10.2	0.9	89.0	8.9	1.0	1.0
Zero	Low	High	1.0	3.7	73.0	22.4	89.0	8.9	1.0	1.0
Zero	Moderate	Zero	33.4	63.4	2.2	1.0	89.0	8.9	1.0	1.0
Zero	Moderate	Low	8.5	82.3	8.3	1.0	89.0	8.9	1.0	1.0
Zero	Moderate	Moderate	2.1	70.7	26.3	1.0	89.0	8.9	1.0	1.0
Low	Low	High	0.9	1.4	66.6	31.0	89.0	8.9	1.0	1.0
Low	Moderate	Zero	10.0	81.8	7.1	1.0	89.0	8.9	1.0	1.0
Low	Moderate	Low	1.4	69.9	27.8	0.9	89.0	8.9	1.0	1.0
Low	Moderate	Moderate	1.0	28.5	68.8	1.8	89.0	8.9	1.0	1.0
Low	Moderate	High	1.0	1.3	52.6	45.2	89.0	8.9	1.0	1.0
Low	High	Zero	1.4	69.7	27.9	1.0	89.0	8.9	1.0	1.0
Low	High	Low	0.9	31.5	66.3	1.3	89.0	8.9	1.0	1.0
Low	High	Moderate	1.0	6.8	83.5	8.6	89.0	8.9	1.0	1.0
Low	High	High	1.0	1.0	27.8	70.2	89.0	8.9	1.0	1.0
Moderate	Zero	Zero	32.9	64.9	1.3	0.9	30.8	66.3	1.9	1.0
Moderate	Zero	Low	8.5	82.7	7.9	0.9	5.4	84.5	9.2	1.0
Moderate	Zero	Moderate	1.8	67.5	29.7	1.0	1.8	65.7	31.4	1.0
Moderate	Zero	High	1.0	1.9	64.2	32.9	0.9	2.8	63.2	33.0
Moderate	Low	Zero	7.0	84.6	7.4	1.0	7.9	82.9	8.3	0.9
Moderate	Low	Low	2.3	70.5	26.1	1.1	2.0	66.6	30.4	1.0
Moderate	Low	Moderate	0.9	34.4	63.0	1.7	1.1	33.1	64.0	1.8
Moderate	Low	High	0.9	1.1	45.2	52.7	0.9	1.3	52.3	45.4
Moderate	Moderate	Zero	1.9	66.4	30.8	0.9	1.9	67.5	29.7	0.9
Moderate	Moderate	Low	1.0	31.6	65.5	1.9	1.1	33.7	63.2	2.0
Moderate	Moderate	Moderate	1.0	6.6	83.9	8.6	1.0	11.8	79.1	8.2
Moderate	Moderate	High	1.0	1.1	32.0	65.8	0.9	1.0	34.0	64.1
Moderate	High	Zero	1.1	29.6	67.2	2.2	1.0	28.8	68.4	1.8
Moderate	High	Low	1.0	7.9	84.5	6.7	1.0	6.1	82.0	10.9
Moderate	High	Moderate	0.9	1.8	64.9	32.4	1.1	1.7	67.2	30.0

FISH_SUBS _DEMAND	MIGRA-TIONS	FISH_ HABITAT	Equation derived CPT				Adjustments based on data			
			Zero	Low	Moderate	High	Zero	Low	Moderate	High
Moderate	High	High	1.1	1.1	20.6	77.3	0.9	0.9	19.8	78.4
High	Zero	Zero	1.0	1.3	55.6	42.1	6.3	86.1	6.7	1.0
High	Zero	Low	0.9	1.1	45.0	53.1	1.8	61.7	35.5	1.0
High	Zero	Moderate	1.0	1.2	36.8	61.0	1.1	31.6	65.9	1.4
High	Zero	High	1.0	1.1	48.4	49.6	0.9	1.1	49.0	49.1
High	Low	Zero	1.1	1.3	42.3	55.4	1.3	62.3	35.5	0.9
High	Low	Low	1.0	1.1	36.1	61.8	1.0	31.1	66.2	1.7
High	Low	Moderate	1.0	1.0	28.9	69.2	1.0	8.6	80.6	9.8
High	Low	High	1.0	1.0	33.3	64.7	1.0	1.1	32.6	65.3
High	Moderate	Zero	1.0	1.1	30.2	67.7	1.0	38.8	58.8	1.4
High	Moderate	Low	1.0	1.0	28.2	69.8	0.9	6.6	81.9	10.5
High	Moderate	Moderate	1.0	1.0	19.3	78.7	1.0	1.7	64.9	32.4
High	Moderate	High	1.0	1.0	19.0	79.0	1.0	1.0	19.4	78.7
High	High	Zero	1.0	1.0	27.6	70.5	1.0	7.3	83.9	7.7
High	High	Low	1.0	1.1	17.5	80.4	1.0	1.8	57.5	39.7
High	High	Moderate	1.1	1.1	16.1	81.7	1.0	1.0	34.3	63.8
High	High	High	1.1	1.1	7.6	90.3	1.1	1.1	10.5	87.3

2.9 Uncertainty

Step 7 of the PROBFLO approach is the evaluation of all aspects of uncertainty associated with the entire BN-RRM process thereby providing context and facilitating the decision-making process in e-flow assessment studies (O'Brien et al 2018). The following contributed to the uncertainty of the outcomes:

- No field assessment was undertaken for this study and the results are based on literature and a desktop e-flow assessment.
- Only limited understanding of flow-ecosystem and flow-ecosystem services relationships for the wetland could be incorporated into the BN modelling. More information on the socio-ecological system processes is required to improve the confidence of the BN model.
- Due to data availability limitations the BN model used to represent the system is simplistic. In an adaptive management context, ecosystem dynamism can be incorporated when the data becomes available.
- Data gained from future monitoring will contribute to confidence of the e-flow assessment.
- The dependency of the hydrodynamic model on rainfall to predict habitat characteristics of the wetland limits the confidence of the discharge wetland inundation relationships. Additional modelling of the discharge and habitat availability in the wetland will improve the confidence of the study.
- The e-flows for the Sudd Wetland are provided to the wetland from the Lake Victoria Nile River and releases from Lake Victoria. The risk regions of the Sudd have been selected to represent potential changes in availability of instream habitats in the wetland and how they may be affected by altered flows from the Nile River. The available hydrodynamic modelling data and relationships between habitat and upstream flows used to determined e-flows for RR1 are directly correlated in the model to the lower wetland and in turn to the flows entering the wetland from the Nile River. Thus, in this desktop assessment the requirements for the upper part of the study area is identical to the downstream RRs. As such we have only evaluated the socio-ecological consequences of altered flows to RR1 and applied these requirements to the other RR2 due to these relationships and available data.

3. RESULTS AND DISCUSSION

The application of the PROBFLO approach has resulted (Figure 9A) initially in the risk to the social and ecological endpoints for the reference scenario for flows observed between 1905 to 1961, These results represent the socio-ecological consequences of altered flows for each month for this period. From these results the risk to all the endpoints have been observed to be within the low range with the risk to the ecological endpoints generally being slightly higher than for the social endpoints, demonstrating that in this case study the ecosystem is more vulnerable to changes in flow than the social endpoints. This is a trend that has been observed throughout Africa (O'Brien et al., 2020 for example in the Inner Niger Delta) and demonstrates how these ecosystems optimise available water, and experience stressful periods even under natural conditions. This is particularly important in these assessments as ecosystems will always utilize/optimise available resources. When this occurs and flows decrease the system may experience some stress but again they have mechanisms' to be resilient to "normal" changes. In these assessments it is the unnatural, anthropogenic changes that we need to manage, and this is what e-flows represent. In Figure 9A temporally variability is considered, here the outcomes include the highest relative risk in March to both the social and the ecological endpoints when compared to the other months. To compare seasonal variations in the reference conditions with other risk scenarios, the March and September data from 1962 to 1982 was compared alone which represent the recovery and high stress seasonal periods in the Coarse e-flow outcomes for B, C and D and the scenarios 0-7 established for this study (Appendix).

The risk outcome distributions are presented as risk profiles representing the range of variability of the risk projections with the median risk used in the evaluations (example in Figure 9). The distributions are relative to each other and background rank range colours have been included to consider the zero (blue) and low risk (green), moderate risk (yellow) but still sustainable and high (red) or unsustainable risk. If the risk distribution extends into the high rank risk zone there would be a probability of that endpoint becoming unsustainable or lost. Again, note that all results can be compared in a relative manner. Initially the seasonal variability in risk associated with monthly flow variability and overall seasonality considerations is included in Figure 9. As expected the flows used to establish the baseline socio-ecological habitat distributions that represent the worst case but natural state of habitats and associated ecosystems result in low to moderate risk distributions for all months considered. Here relative vulnerabilities of the social vs. ecological endpoints emerge with a relatively more vulnerable ecosystem compared to social endpoints as described above. This is expected as the biodiversity and ecosystem processes that represent the ecosystem wellbeing are relatively more complex and dynamic that the ecosystem services these systems provide. In addition the birds and invertebrates have been identified as more vulnerable components or indictors of the ecosystem. These results represent the seasonal variability of risk responses and demonstrate that if March and September results are considered we can represents the whole year of variability in the risk outcomes where March represents dry parts of each season and wet represents the wet part. In Figure 9B synopsis relative risk profiles of the historically observed dry (1905-1961) and wet (1962 to 1982) phases observed, and the B, C and D e-flows requirements proposed for the White Nile and summary of option 0-7 for wet and dry periods are presented. These outcomes represent the range of variability for the study and include some scenarios that would result in unacceptably high-risk including Class C and D coarse E-flow projections and options 0-7.

Some of these risk distributions are however misrepresentations of the net effect of flows entering the Sudd as precipitation that falls onto the wetland has been included in all of the hydrodynamic modelling. To separate the effect of upstream flows into the Sudd compared to the contribution that rainfall makes to habitat availability we have compared option 0-7 with and without rain in Figure 10 to Figure 17. Results are extremely variable and demonstrate that when rainfall is removed if we use the habitat availability associated with the 1905-1961 reference dry phase flow phase as a baseline which includes rainfall that all scenarios without rainfall would result in significant, unsustainable conditions for the wetland. Due to the size of the Sudd and its location precipitation makes a significant contribution to the water levels in the wetland. These results contribute to the consideration of climate change in the study area especially for reduced rainfall scenarios that may result in catastrophic changes and loses to the ecosystems and ecosystem services in the wetland. In this study however we are concerned with altered upstream flows affecting the availability of water within the wetland and associated conditions of the socio-ecological system that depends on this water in the wetland. This has been achieved in the form of the determination of water required from the White Nile to be released into the Sudd during "normal" or experienced wet and dry rainfall variability.

Finally, we can consider unacceptable relative risk associated with individual scenarios to the social and ecological endpoints considered in the study. Outcomes include any social or ecological endpoint that will result in high risk. These include Option 1 (year 1 and 2) (Figure 11), Option 2 for March (dry season) for years 1 and 2 (Figure 12) and Option 6 (Figure 16). These results demonstrate that while the wetland is resilient to changes in input flows from the White Nile River, extreme and extended reductions in flows can render the system unsustainable. Floodplain ecosystems are dynamic productive ecosystems that are highly productive and establish dynamic habitats that maintain ecosystems and the services people derive from them (Opperman et al., 2017). In this study using NBI (2019a) we used our existing understanding of the open water, aquatic vegetation, fringe vegetation, papyrus marsh, reedbeds, grassland and trees and shrubs dominated wetland habitats to represent the variability of wetland habitats for this assessment. In addition we used our understanding of how attributes associated with the availability of water in the wetland and the condition of these habitats to evaluate the condition of the endpoints selected for the study (Table 5). With this information we have demonstrated that the diversity of habitats within the Sudd are affected by upstream flows and that when flows are altered significantly the availability of habitats and associated condition of the wetland deteriorates. The hydrodynamic model used in the e-flow assessment has been foundational to this assessment which considers the volumes, timings and durations of flows that enter the Sudd. This model has been calibrated using observed flows so that the dynamism of the water flow retention (controls) within the Sudd can be considered, with some associated uncertainty. Floodplain ecosystems act as massive sponges that retain water (Opperman et al., 2017; O'Brien et al., 2020). These sponge like ecosystems may require more than one season of "normal" flows to become fully saturated and may retain water and contribute to low flow maintenance during low flow years as a result of previous saturations. In a recent evaluation of the wetlands on the lower Mara River flows observed entering the wetland upstream of Lake Victoria were significantly lower than flows being released from the wetland due to previous season flows that had been retained in the saturated wetland (O'Brien et al., 2018). While this provides some resilience to the wetlands and its habitats if low flows persist and the wetland does not recover (becomes saturated) its function and condition deteriorates.

In this study we have demonstrated that these processes can occur when input flows from the White Nile River are altered, resulting in significant changes to instream habitats and the condition of the ecological and social endpoints considered in the study.

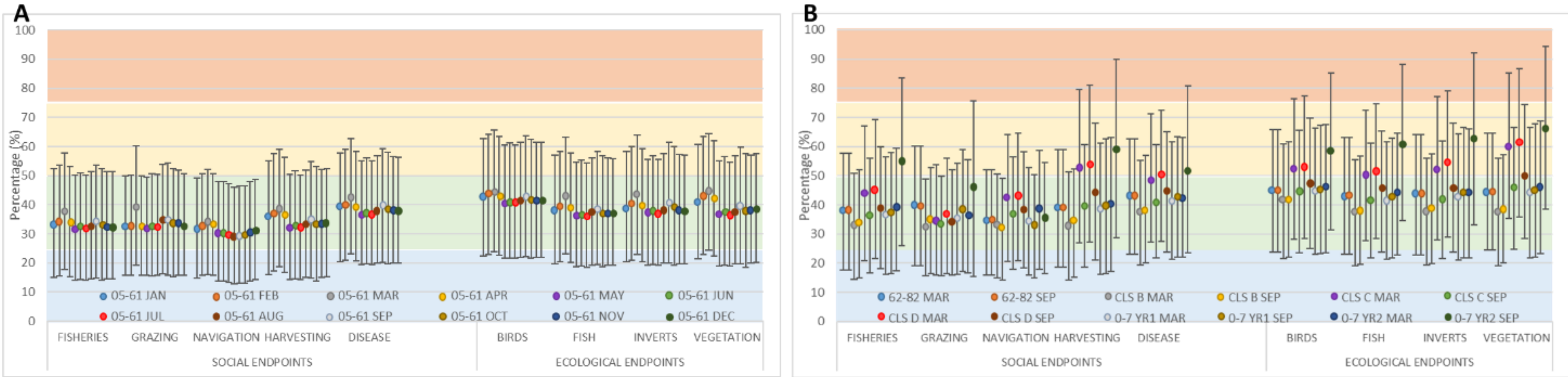

Figure 9: Relative risk outcomes representing the socio-ecological consequences of altered flow scenarios to the social and ecological endpoints considered in the study. Graph background colours represent zero (blue) and low risk (green), moderate risk (yellow) but still sustainable and high (red) or unsustainable risk. Summary of all scenarios including risk of reference flows for January to December (Graph A) and March and September flows for wet phase (1962-1982), Class B, C and D flows determined in the Coarse E-flow assessment (O'Brien et al., 2019) and summary scenarios developed for this case study Options 0-7 for year 1 and Year 2 (Appendix).

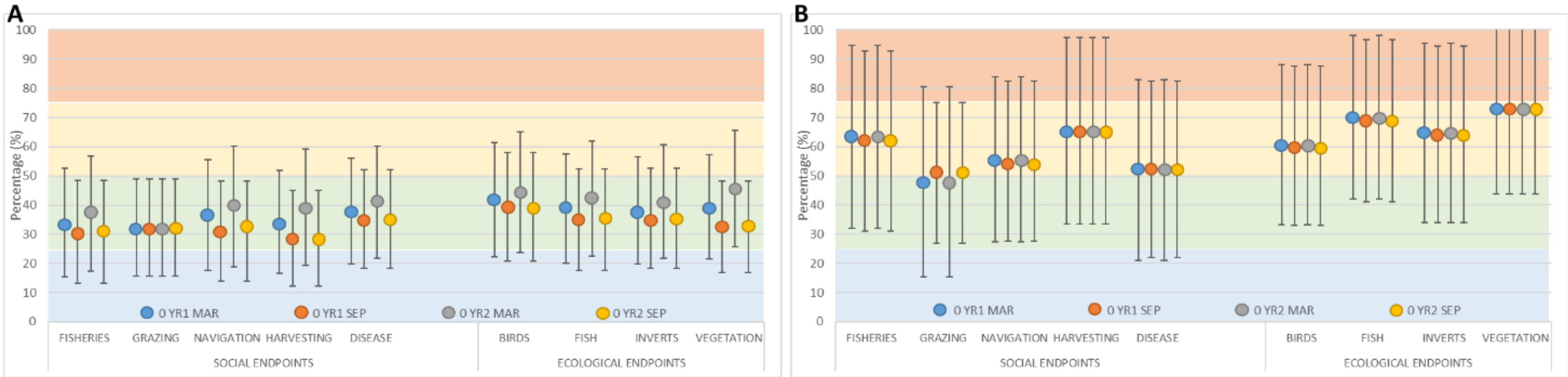

Figure 10: Relative risk outcomes representing the socio-ecological consequences of altered flow scenarios to the social and ecological endpoints considered in the study. Graph background colours represent zero (blue) and low risk (green), moderate risk (yellow) but still sustainable and high (red) or unsustainable risk. Results for Option 0 Year 1 & 2 with rainfall (Graph A) and without rainfall (Graph B) for March and September.

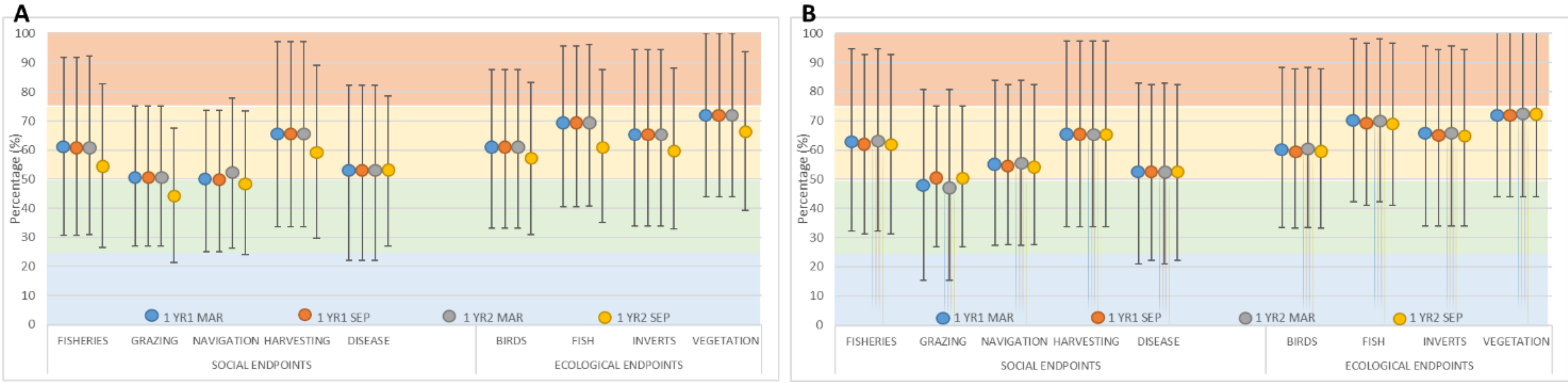

Figure 11: Relative risk outcomes representing the socio-ecological consequences of altered flow scenarios to the social and ecological endpoints considered in the study. Graph background colours represent zero (blue) and low risk (green), moderate risk (yellow) but still sustainable and high (red) or unsustainable risk. Results for Option 1 Year 1 & 2 with rainfall (Graph A) and without rainfall (Graph B) for March and September.

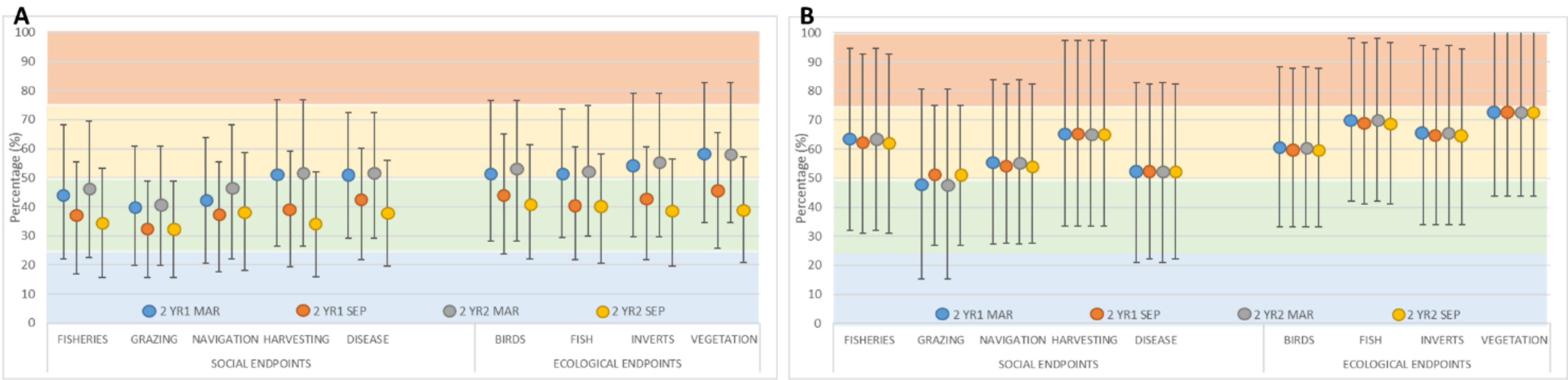

Figure 12: Relative risk outcomes representing the socio-ecological consequences of altered flow scenarios to the social and ecological endpoints considered in the study. Graph background colours represent zero (blue) and low risk (green), moderate risk (yellow) but still sustainable and high (red) or unsustainable risk. Results for Option 2 Year 1 & 2 with rainfall (Graph A) and without rainfall (Graph B) for March and September.

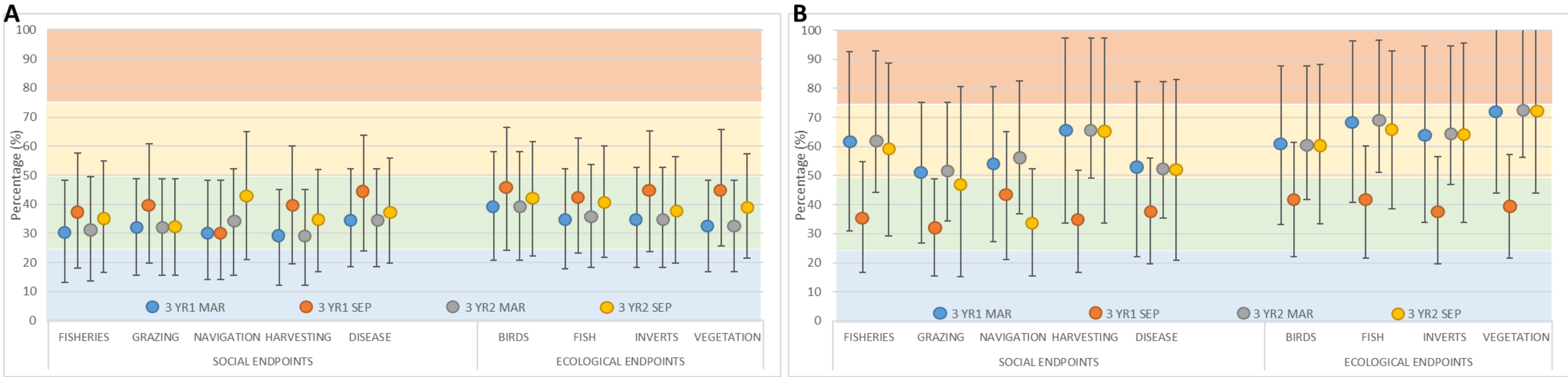

Figure 13: Relative risk outcomes representing the socio-ecological consequences of altered flow scenarios to the social and ecological endpoints considered in the study. Graph background colours represent zero (blue) and low risk (green), moderate risk (yellow) but still sustainable and high (red) or unsustainable risk. Results for Option 3 Year 1 & 2 with rainfall (Graph A) and without rainfall (Graph B) for March and September.

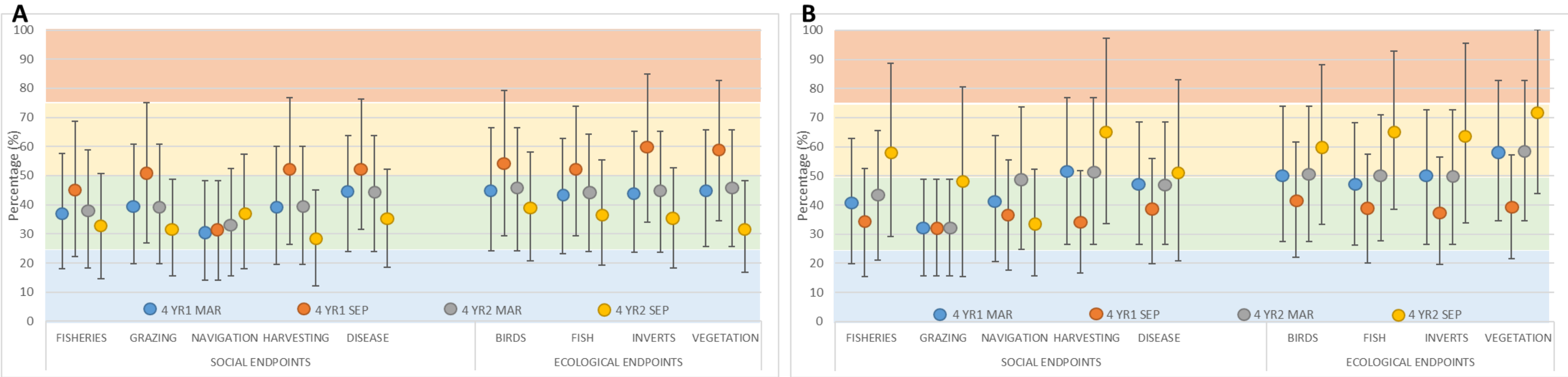

Figure 14: Relative risk outcomes representing the socio-ecological consequences of altered flow scenarios to the social and ecological endpoints considered in the study. Graph background colours represent zero (blue) and low risk (green), moderate risk (yellow) but still sustainable and high (red) or unsustainable risk. Results for Option 4 Year 1 & 2 with rainfall (Graph A) and without rainfall (Graph B) for March and September.

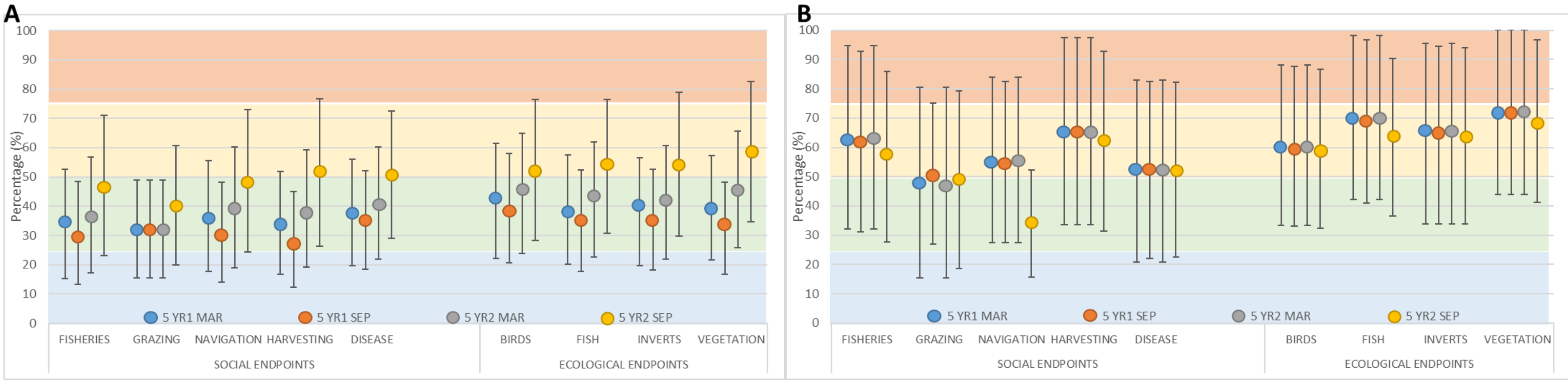

Figure 15: Relative risk outcomes representing the socio-ecological consequences of altered flow scenarios to the social and ecological endpoints considered in the study. Graph background colours represent zero (blue) and low risk (green), moderate risk (yellow) but still sustainable and high (red) or unsustainable risk. Results for Option 5 Year 1 & 2 with rainfall (Graph A) and without rainfall (Graph B) for March and September.

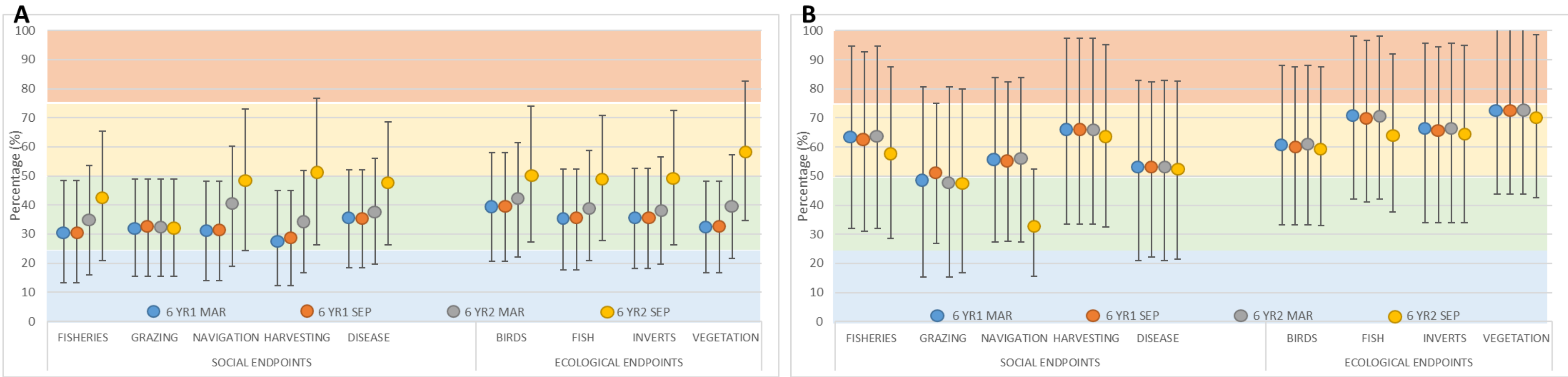

Figure 16: Relative risk outcomes representing the socio-ecological consequences of altered flow scenarios to the social and ecological endpoints considered in the study. Graph background colours represent zero (blue) and low risk (green), moderate risk (yellow) but still sustainable and high (red) or unsustainable risk. Results for Option 6 Year 1 & 2 with rainfall (Graph A) and without rainfall (Graph B) for March and September.

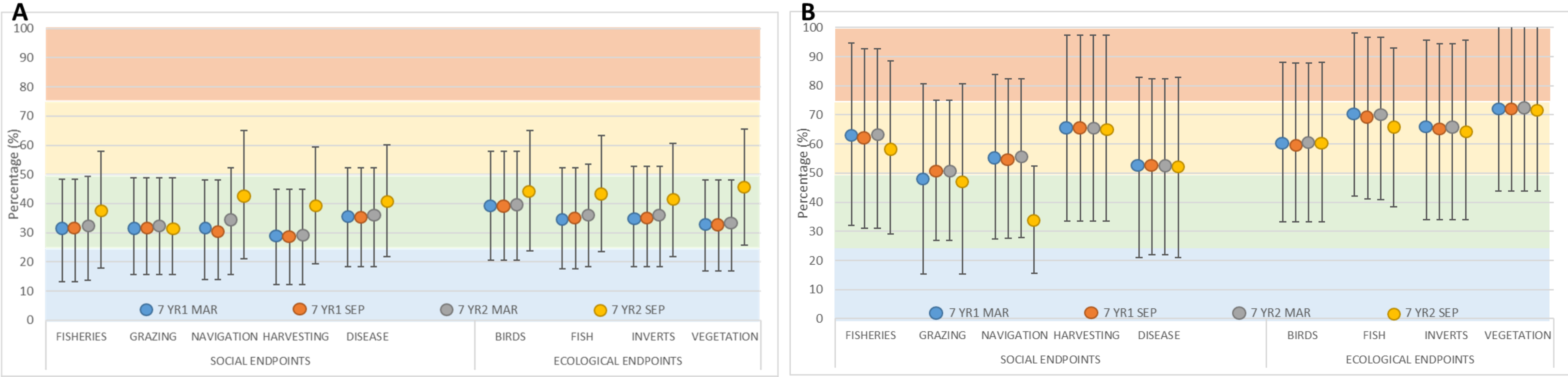

Figure 17: Relative risk outcomes representing the socio-ecological consequences of altered flow scenarios to the social and ecological endpoints considered in the study. Graph background colours represent zero (blue) and low risk (green), moderate risk (yellow) but still sustainable and high (red) or unsustainable risk. Results for Option 7 Year 1 & 2 with rainfall (Graph A) and without rainfall (Graph B) for March and September.

Based on this assessment, where the socio-ecological consequences of a series of scenarios were evaluated, the e-flow assessment for Class B for the coarse e-flow assessment study (NBI, 2019c) is comparable with the minimum input flows required to maintain the Sudd Wetland in a suitable state. The outcome data includes a flow-duration or flow/exceedance table (Table 10) and flow distribution graph. This relates to an annual e-flow requirement of 52% of the MAR (or 26 024MCM) of the White Nile, where 45.8% (22 932MCM) of the requirement is for low flows and 6.2% (3 091 MCM) for floods.

Table 10: Flow duration table/exceedance table with percentiles representing flow requirement for the Sudd wetland.

Percentiles	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.1	859	923	842	871	981	1024	1086	1228	1308	1092	1051	862.7
1	859	923	842	871	981	1024	1086	1228	1308	1092	1051	862.7
5	859	923	842	871	981	1024	1086	1228	1308	1092	1051	862.7
10	859	923	842	871	981	1024	1075	1210	1283	1092	1051	862.7
15	859	923	842	871	981	1024	1063	1193	1258	1092	1051	862.7
20	857	921	840	869	980	1023	1051	1175	1234	1090	1049	862.2
30	849	913	835	864	973	1017	1027	1141	1195	1082	1037	860.7
40	837	890	822	849	962	1010	999.7	1113	1138	1065	1024	858.5
50	817	872	811	836	943	998	981.8	1085	1112	1048	983.8	856.5
60	770	832	788	803	904	978	946.9	1026	1007	991.3	935.6	852.6
70	696	748	726	751	834	924	885.7	980.7	938	923.5	870.2	839.7
80	592	635	637	659	720	836	802.3	867.6	808	852.6	842.4	808.2
85	534	573	581	601	648	771	740.8	798.7	725.3	846.4	815.3	782.2
90	480	514	519	537	569	689	663.2	712	635	833.9	766.3	735
95	434	464	457	473	490	591	569.7	607.3	542.7	786.3	660.7	632.8
99	407	435	414	429	435	502	485.8	513.5	449.3	487.3	468.2	437
99.9	401	429	404	418	422	482	466.9	492.4	428.3	420.1	424.9	392.9

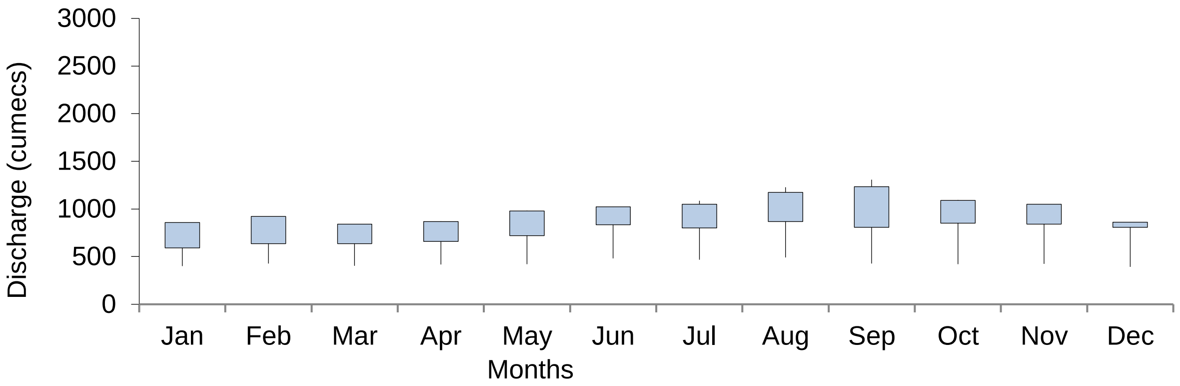

Figure 18: E-flow requirement for the inflow of water from the Victoria Nile into the Sudd Wetland using box and whisker plots (box 20-80%tiles) and whisker 0.01%tiles and 99.9%tiles.

The sustainable management of the Sudd wetland supports the socio-ecological wellbeing of the entire White Nile and Nile River below the confluence with the Blue Nile River. The wetland provides valuable habitats for a large portion of the fauna and flora of the basin and refuge habitat for species that migrate upstream and downstream of the wetland. The ecosystem processes including a range of regulatory services that the wetland provides also maintains the wellbeing of the White Nile and Nile Rivers. This ecosystem and the services it provides to local residents and the people of the basin as a whole must be managed in a sustainable manner to ensure that the services it provides locally and regionally are maintained.

The NBI seeks to develop the Nile River in a co-operative manner so as to share the socio-economic benefits that occur from the development of these transboundary water resources (NBI, 2013). In the wetland management strategy (NBI, 2013) of the NBI, the implementation of an ecosystem approach to the management of wetlands in the basin, including the Sudd, where the ecosystem's benefits and services are maintained to conserve biodiversity and ensure human well-being in the future is relevant. Significant changes in the flows released into the wetland will result in socio-ecological risk that can be avoided if e-flows are provided to the system. This will have local and regional benefits and offer regional stakeholders opportunities for additional sustainable development of resources if the Sudd ecosystem is maintained and continues to provide its services. This will contribute to the achievement of the equitable wetland resource use by supporting the development of e-flow regulations to ensure that wetlands users consider the potential impacts of developments on the sustainability of the wetland. Towards this the outcomes of this e-flow determination study directly contributes to the objectives of the Water Management Strategy (NBI, 2013) including the provision of knowledge on wetlands of transboundary importance in the Nile Basin to support basin-wide conservation, management, planning and restoration efforts (Objective 1). Promotion of awareness and research to build consciousness around the important role of wetlands and their ecosystem functions for the basin's development (Objective 2). This is being achieved through this and other monograph outcomes pertaining to the wetlands of the Nile, including the Sudd. Development of sustainable and cooperative management mechanisms including e-flows for wetlands (Objective 3). Through the application of these objectives in this study a contribution to the management of the Nile Basin as a whole can be supported.

The e-flow requirements provided in this assessment (Table 10) provides users with the volumes, timing and duration of flows required as a minimum for water releases into the Sudd Wetland. This information can contribute to the determination of flow release requirements and contribute to water resource allocation upstream of the Sudd. This information can also be directly integrated into the NileDSS which will consider these requirements as a control/limit in the allocation of water resources in the basin. The uncertainty associated with this assessment can be reduced, and the risk assessment can be improved in an adaptive management context where new information generated for the Sudd is incorporated into the assessment and the proposed socio-ecological consequences of altered flows are tested/monitored. This should include consideration of flow-ecosystem and flow-ecosystem service relationships used in this study when real evidence is provided. These relationships can also be integrated into a monitoring plan for the wetland that can later contribute to improved outcomes and their application. The holistic risk assessment undertaken in this study is based on available information that has largely been modelled. This should be replaced overtime with real data from the wetland which would have a great cost-benefit when the value of the services the wetland provides is considered. This should support these management process and again reduce uncertainty.

4. CONCLUSION

In this study the PROBFLO approach has been successfully implemented to evaluate the socio-ecological consequences of altered flows to the Sudd Wetland and provide and adequate e-flow scenario that can represent a sustainable balance between the use and protection of the water resources of the Sudd Wetland and associated upstream resources of the White Nile River. The e-flow requirements determined for the Sudd relates to an annual flow requirement of 52% of the MAR (or 26 024MCM) of the White Nile, including 45.8% (22 932MCM) of the requirement for low flows and 6.2% (3 091 MCM) for floods. This requirement is comparable with the Class B flow requirements established in the coarse e-flow assessment for sites in the Nile Basin. Outcomes of the study also demonstrate the socio-ecological consequences of a range of altered flow scenarios, some of which would have significant negative impacts to the wellbeing of the wetland ecosystems and the services it provides resulting in an unsustainable condition. The PROBFLO assessment with rainfall resulting in the establishment of e-flow requirements of 58% of the MAR will maintain social and ecological attributes in the wetland and meet biodiversity and ecosystem service requirements of stakeholders.

The sustainable management of the Sudd wetland supports the socio-ecological wellbeing of the entire White Nile and Nile River below the confluence with the Blue Nile River. The wetland provides valuable habitats for a large portion of the fauna and flora of the basin and refuge habitat for species that migrate upstream and downstream of the wetland. The ecosystem processes including a range of regulatory services that the wetland provides also maintains the wellbeing of the White Nile and Nile Rivers. This ecosystem and the services it provides to local residents and the people of the basin as a whole should be managed in a sustainable manner to ensure that the services it provides locally and regionally are maintained. Significant changes in the flows released into the Sudd will result in socio-ecological risk that can be avoided if e-flows are provided to the system. This will have local and regional benefits and offer regional stakeholders opportunities for additional sustainable development of resources if the Sudd ecosystem is maintained and continues to provide its services. This will contribute to the achievement of the equitable wetland resource use by supporting the development of e-flow regulations to ensure that wetlands users consider the potential impacts of developments on the sustainability of the wetland. Towards this the outcomes of this e-flow determination study directly contributes to the objectives of the Water Management Strategy. Through the application of these objectives in this study a contribution to the management of the Nile Basin as a whole can be supported.

High uncertainty identified in the study can be mitigated through evidence based, adaptive management and collection and incorporation of new data. This approach, with similar applications in the Inner Niger Delta (O'Brien et al, 2020) and Phongolo Floodplains (O'Brien et al, 2021), is robust and can be considered good practice for the determination of e-flows of wetlands in Africa.

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