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A regional scale ecological risk framework for environmental flow evaluations.

Gordon C. O'Brien[1*], Chris Dickens[2], Eleanor Hines[3], Victor Wepener[4], Retha Stassen[1] and Wayne G. Landis[3].

[1]University of KwaZulu-Natal, College of Agriculture, Engineering and Science, School of Life Sciences, Private Bag X01, Scottsville, South Africa.

[2]International Water Management Institute, Private Bag X813, Silverton, 0127, South Africa.

[3]Western Washington University, Institute of Environmental Toxicology, Bellingham, Washington, USA

[4]Water Research Group (Ecology), Unit for Environmental Sciences and Management, North-West University, Private Bag x6001, Potchefstroom 2520, South Africa

Correspondence to: Gordon C. O'Brien (obrieng@ukzn.ac.za)

Abstract.

Recent developments in Environmental Flow (E-flow) frameworks advocate holistic, regional scale, probabilistic E-flow assessments that consider flow and non-flow drivers of change in socio-ecological context as best practice. Regional Scale ecological risk assessments of multiple sources, stressors and diverse ecosystems that address multiple social and ecological endpoints, have been undertaken internationally at different spatial scales using the relative-risk model since the mid 1990's. With the recent incorporation of Bayesian belief networks into the relative-risk model, a robust regional scale ecological risk assessment approach is available that can contribute to achieving the best practice recommendations of E-flow frameworks. PROBFLO is a regional scale, holistic E-flow assessment method that incorporates the relative-risk model and Bayesian belief networks (BN-RRM) into a transparent probabilistic modelling tool that addresses uncertainty explicitly. PROBFLO has been developed to holistically evaluate the socio-ecological consequences of historical, current and future altered flows in the context of non-flow drivers and generate E-flow requirements on regional scales spatial scales. The approach has been implemented in two regional scale case studies in Africa where its flexibility and functionality has been demonstrated. In both case studies the evidence based outcomes facilitated informed environmental management decision making, in the context of social and ecological aspirations. This paper presents the PROBFLO approach as applied to the Senqu River catchment in Lesotho and further developments and application in the Mara River catchment in Kenya and Tanzania. The ten BN-RRM procedural steps incorporated in PROBFLO are demonstrated with examples from both case studies. Outcomes allowed stakeholders to consider sustainable social and ecological E-flow trade-offs between social and ecological endpoints.

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PROBFLO can be incorporated into adaptive management processes and contribute to the sustainable management of the use and protection of water resources.

Keywords: PROBFLO, Environmental Flows, Regional Scale ecological risk assessments, E-flow requirements, socio-ecological consequences, trade-offs, sustainable water resource management.

1 Introduction

The global use of water resources has altered the wellbeing of aquatic ecosystems and the benefits that people derive from these ecosystems (Acreman and Dunbar, 2004; Dudgeon et al., 2006; Growns, 2008; Vörösmarty, 2010; Isaak et al., 2012; Isaak et al., 2012; Murray et al., 2012; Grafton et al., 2013; Dudgeon, 2014); Environmental flows (E-flows), according to the Brisbane Declaration (2007) are defined as the 'quantity, timing and quality of water flows required to sustain **f**reshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems'. The international community has developed a plethora of E-flows assessment methods which have been applied on numerous spatial scales in a wide range of ecosystem types across the globe (Tharme 2003; Acreman and Dunbar 2004; Pahl-Wostl et al., 2013; Poff and Matthews 2013). These methods have evolved over time and in a review of their development Poff and Matthews (2013) identified three distinct periods of E-flow research and developmental history. These periods include the emergence and synthesis period, consolidation and expansion period and the current globalisation period. During this globalisation period a range of best practice E-flow management and assessment principles, and associated frameworks to undertake E-flow on multiple spatial scales in multiple political and or legislative contexts have been developed (Poff et al. 2010; Pahl-Wostl et al. 2013). These principles promote the use of holistic assessment tools that consider both social and ecological features of ecosystems on regional spatial scales, are adaptive and incorporate risk evaluation and address uncertainty (Poff et al. 2010; Acreman et al. 2014).

Ecological risk assessment of multiple sources of stressors, multiple stressors and diverse ecosystems that address multiple social and ecological endpoints, have been undertaken internationally at different spatial scales using the relative-risk model (RRM) established since the mid 1990's (Hunsaker et al. 1990; Landis and Weigers 1997; 2007; Wiegers et al., 1998; Landis 2004; Landis, 2016). The RRM has been applied to evaluate a range of natural and anthropogenic stressors including water pollution, diseases, alien species and a range of altered environmental states (Walker et al., 2001; Moraes et al., 2002; Hayes and Landis, 2004; Colnar and Landis, 2007; Anderson and Landis, 2012; Ayre and Landis, 2012; Bartolo et al., 2012; O'Brien et al., 2012.; Hines and Landis, 2014; Ayre et al., 2014). Bayesian Networks (BN) have become established as a powerful tool for ecological risk assessment, ecosystem management and E-flow assessment (Pollino et al., 2007; Hart and Pollino, 2008; Shenton et al., 2011; Chan et al., 2012; Pang and Sun, 2014; Liu et al., 2016, McDonald et al., 2016). In 2012 Ayre and Landis

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combined both approaches and incorporated BNs into RRMs which was then formalised into a BN-RRM approach (Hines and Landis 2014; Herring et al., 2015; Landis et al., 2016).

Between 2013 and 2016 a BN-RRM based holistic E-flow assessment approach has been established that adheres to the principles of best E-flow management practice (Ayre and Landis, 2012), and can easily be incorporated into regional E-flow frameworks such as the Ecological Limits of Hydrologic Alteration framework (Poff et al., 2010). This BN-RRM approach, called PROBFLO, is transparent and adaptable, can use available data and expert opinion and explicitly addresses uncertainty. PROBFLO is scenario based and allows for the evaluation of the socio-ecological consequences of altered flows with consideration of the synergistic effects of non-flow drivers of ecosystem impairment. The approach is transparent and adaptable and allows acceptable risk trade-off considerations for a range of environmental management options. This paper presents the PROBFLO BN-RRM approach as applied to the Senqu River in Lesotho and further development were made in the Mara River in Kenya and Tanzania.

2 Study area

The Lesotho Highlands Water Project (LHWP) is a US$ multi-billion water transfer and hydro-power project implemented by the governments of Lesotho and South Africa. Phase 1 of the LHWP included the application to the impacted rivers of the DRIFT E-flow method to manage the downstream water releases from the Katse and Mohale Dams (Arthington et al., 2003). Phase 2 involves the augmentation of the LHWP by construction of the Polihali Dam to divert water directly from the upper Senqu River to the existing Phase 1 infrastructure of the LHWP (Figure 1). The PROBFLO approach has been applied to the Senqu River in Lesotho as a part of Phase 2 of LHWP between the proposed Polihali Dam site (29.289593°S; 28.863890°E) and the border of South Africa (30.413231°S; 27.564090°E) (LHDA, 2016).

The entire Mara River in Kenya and Tanzania upstream of the mouth into Lake Victoria (1.518178°S; 33.943497°E) was considered in this regional scale PROBFLO case study (NBI, 2016) (Figure 2). The Mara River and its tributaries are an essential source of water for domestic needs, agriculture, pastoralism and wildlife including tourism, in Kenya and Tanzania (Mati et al., 2008; Defersha and Melesse, 2012). Although extensive research has been undertaken into the environmental management of the Serengeti and Mara nature reserves in the Mara Basin and the effects of land use threats, limited consideration has been given to stream-flow management (Broten and Said, 1995; Gereta et al., 2002; Onjala, 2002; Karanja, 2003; Lamprey and Reid, 2004; Hoffman, 2007; Mati et al., 2008; Atisa, 2009; LVBC and WWF-ESARPO, 2010; Majule, 2010; Hoffman et al., 2011; Ogutu et al., 2011; Defersha and Melesse, 2012; Kiambi et al., 2012; Dessu et al., 2014).

3 PROBFLO Framework for E-flows

The PROBFLO framework is based on the ten procedural RRM steps (Landis, 2004a), and incorporates BN development and evaluation procedures (Marcot et al., 2006; Ayre and Landis, 2012), into a robust E-flow assessment method that gives emphasis to adaptive management for holistic E-flow management (Figure 3). The application of the PROBFLO model in the Senqu and Mara River case studies is used here to demonstrate the application of the procedural steps.

Step 1: Vision exercise

The importance of having clear water resource management objectives cannot be over-emphasised. Numerous Integrated Water Resource Management strategies, regional management plans and frameworks, national legislations, and established E-flow assessment tools advocate the establishment of clear goals or visions to direct the use and protection of water resources (Biswas 2004; Mitchell, 2005; Dudgeon et al., 2006; Richter et al., 2006; Poff et al., 2010; King and Pienaar 2011; NBI, 2016). Although many vision development approaches are available, the initial application of PROBFLO involved the application of the Resource Quality Objectives (RQO) determination procedure (DWA, 2011) to describe and document the water quality, water quantity, habitat and biota objectives for the water resource being evaluated (NBI 2016; DWA, 2011). The RQO process results in narrative and numerical descriptions of various ecosystem features required to achieve a balance between the use and protection of resources and hence to achieve a documented vision. As part of the initial development of the RRM approach, multiple social and ecological endpoints were evaluated in a relative manner (Wiegers et al., 1998). The PROBFLO approach incorporates this foundation to evaluate a range of socio-ecological endpoints. In these case studies only those social and ecological endpoints that were directly associated with the river and those that would be influenced by the flow of the river were considered.

The vision of the Senqu River case study was based on the requirements of a Treaty for the LHWP entered into by the Kingdom of Lesotho and the Republic of South Africa for the purpose of bringing about this water resource development. The Treaty gives emphasis to protection of the existing quality of the environment and, in particular, requires maintenance of the wellbeing of persons and communities immediately affected by the project, including those downstream of the dam. Accordingly, the vision states that there should be no change to the existing quality of the downstream environment and that the net effect of the dam should not be negative to the people living downstream of the dam. For the PROBFLO assessment, RQOs describing the desired quality and quantity of water, habitat and biota for the study area were established. The endpoints selected to represent the social and ecological management objectives for the PROBFLO assessment were based on the vision represented by the RQOs in the case study including the maintenance of the following ecosystem services and ecological objectives affected by the river: (1) the supply building sand from the Senqu River, (2) water for domestic use, (3) recreation/spiritual use of the river, (4) fish stocks as food for people, (5) edible plants from the riparian zone as food for people, (6) medicinal

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plants for people, (7) floodplain non-woody plants (for grazing), (8) woody plants for fuel and construction , (9) reeds for construction and (10) fish and (12) aquatic marco-invertebrate communities and (12) riparian ecosystem wellbeing.

The vision for the Mara River case study was based on existing regional trans-boundary Mara River management objectives (WRMA, 2014). In 2014, a Catchment Management Strategy (CMS) for the Mara Basin in Kenya was developed to facilitate the management of the water resources, environment and human behaviour in ways that achieve equitable, efficient and sustainable use of water for the benefit of all users (WRMA, 2014). The aims of the Mara River Basin as part of the Strategic Environmental Assessment (EAC, 2003) to maintain "the people living in harmony with nature while achieving human wellbeing and sustainable economic development in perpetuity" were also considered. Also considered were the objectives for the Mara River Basin as described by the Biodiversity and Strategy Action Plan which describes "a region rich in biodiversity which benefits the present and future generations and ecosystem functions" (LVBC & WWF-ESARPO, 2010). These assessments established a high ecological importance, high livelihoods value and low commercial value vision for the upper Mara River Basin and a high ecological importance, moderate livelihoods value and moderate commercial value vision for the lower Mara River Basin. In this context the endpoints selected for the study included: (1) to provide water for Basic Human Needs according national legislation of Kenya and Tanzania, (2) to maintain the ecological integrity of the riverine ecosystem (instream and riparian ecosystems), (3) to provide flows for the commercial production of crops, (4) the maintenance of existing livestock industry, (5) the maintenance and wellbeing of the Eco-tourism industry, and (6) maintain the ecological integrity of the Mara Wetland in the lower reaches of the basin.

3.2 Step 2: Mapping and data analyses

The BN-RRM approach that forms the basis of PROBFLO includes the relative evaluation of multiple sources of stressors to endpoints on a regional scale which should be spatially and temporally referenced for regional comparisons/evaluations in a PROBFLO assessment (Landis 2004a; Landis & Wiegers 2007). For this the spatial extent of the study area must be defined and described, and the locations of potential sources, habitats and impacts must be identified and spatially referenced. In addition, source-stressor exposure and habitat/receptor to endpoint pathways/relationships should be spatially referenced where possible (O'Brien & Wepener 2012; Landis et al. 2016). Available data describing the ecosystem needs to be reviewed and spatially referenced and the uncertainties associated with the availability and quality of data used in the assessment must be documented for evaluation in Step 7. O'Brien & Wepener (2012) provide an approach to delineate ecosystem types, the topological features of importance, the catchment and ecoregion boundaries, the land or water resource use scenarios and the pathways of stressors exposure. This approach is used to direct the selection of risk regions for assessment. Best practice E-flow frameworks accentuate the importance of ecosystem type classification as part of E-flow assessments to improve on our understanding of flow-ecosystem relationships (Poff et al., 2010).

3.3 Step 3: Risk region selection

In this step combinations of the management objectives, source information, and habitat data are used to establish geographical risk regions that can be assessed in a relative manner (Landis 2004b; O'Brien and Wepener, 2012) . In the end, the outcomes of the assessment will be available at the spatial scale established during this step for multiple temporal scenarios associated with alternative management options. In this regard it is important to consider the spatial connectivity of multiple variables including flows and other variables within the study area so that risk regions incorporate appropriate sources, stressors, habitats and endpoints (Landis 2004b; O'Brien and Wepener 2012). The approach can address spatial and temporal relationships of variables between risk regions, such as the downstream effect of a source on multiple risk regions, in the context of the assimilative capacity of the ecosystem or the upstream connectivity requirements of a migratory fish between risk regions.

The selection of risk regions for the Senqu River E-flow assessment was based on the proposed location of the Polihali Dam and catchment boundaries of the Senqu River and large tributaries (Malibamatso and Senqunyane Rivers) for this E-flow assessment. Physical access to sampling sites within Lesotho to conduct bio-physical field surveys were extremely difficult and this also contributed to risk region selection. Four broad risk regions were selected for the Senqu River PROBFLO study (Figure 1).

In the Mara River case study a review of ecosystem types (Mati et al., 2008; Atisa et al., 2014), hydrology (Mango et al., 2011; McClain et al., 2014), the vision for the case study, current and future land and water resource use options and socio-ecological importance (Karanja, 2002; LVBC & WWF-ESARPO, 2010; Mango et al., 2011; Defersha and Melesse, 2012; Dessu et al., 2014; Dutton et al., 2013), were used to select risk regions during a stakeholder workshop . Ten Risk Regions were selected for the Mara River Case study which conformed to catchment boundaries, ecoregions, land use practices and the international boundary (Figure 2).

3.4 Step 4: Conceptual model

In this step conceptual models that describe hypothesised relationships between multiple sources, stressors, habitats and impacts to endpoints selected for the study are generated (Wiegers et al., 1998) (Figure 4). This includes the holistic (consider flow and non-flow related variables in spatial-temporal context), best practice characterisation of flow-ecosystem and flow-ecosystem service relationships in the context of a regional scale E-flows framework (Poff et al., 2010), with relevant non-flow (water quality and habitat) relationships in the models. Conceptual models should be constructed by expert stakeholders usually including hydrologists, geomorphologists, ecologists and ecosystem service, including social and resource economics

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scientists. These experts should be familiar with socio-ecological system processes and be able to describe probable cause and effect variables and relationships of sources to stressors to multiple receptors in relation to their impacts on the endpoints, selected for the study. The conceptual models for the case studies presented addressed requirements of the ELOHA and the Nile Basin regional scale E-flow frameworks to conform to these frameworks (Poff et al., 2010; NBI, 2016). The Nile Basin regional scale E-flow framework expands on the ELOHA framework to include an initial situation assessment, data review and alignment phase and a governance and Resource Quality Objectives setting phase. The PROBFLO conceptual model thus conforms to the regional scale E-flow framework procedures in: (1) the selection of socio-ecological endpoints, to direct the hydrologic foundations for the study including the selection of hydrological statistics required, (2) to classify ecosystem types based on geomorphic, water quality, quantity and ecoregion considerations, and with this data, (3) to determine the holistic flow-ecosystem and flow-ecosystem service, with relevant non-flow variable relationships upon which the assessment is based. Initial conceptual model development considers all relevant sources, stressors, habitat, effects and impact relationships with spatial and temporal considerations.

3.5 Step 5: Ranking scheme

Ranking schemes are used to represent the state of variables, with unique measures and units to be comparable as non-dimensional ranks and combined in BN-RRMs (Landis, 2004a; Landis et al., 2016). Four states designated as zero, low, moderate and high as traditionally used in RRMs (Colnar & Landis, 2007; O'Brien and Wepener, 2012; Hines & Landis 2014; Landis et al. 2016), have been incorporated into the PROBFLO process. The states represent the range of wellbeing conditions, levels of impacts and management ideals as follows:

- Zero: pristine state, no impact/risk, comparable to pre-anthropogenic source establishment, baseline or reference state,
- Low: largely natural state/low impact/risk, ideal range for sustainable ecosystem use,
- Moderate: moderate use or modified state, moderate impact/risk representing threshold of potential concern or alert range, and
- High: significantly altered or impaired state, unacceptably high impact/risk.

This ranking scheme selected for PROBFLO represents the full range of potential risk to the ecosystem and ecosystem services with management options. Low risk states usually represent management targets with little impact and moderate risk states represent partially suitable ecosystem conditions that usually warrant management/mitigation measures to avoid high risk conditions. The incorporation of BN modelling into PROBFLO, allows the approach to incorporate the variability between ranks for each model variable, represented as a percentage for each rank. Indicator flow and non-flow variables representing the socio-ecological system being evaluated in a PROBFLO assessment are selected (linked to endpoints – step 1), and unique measures and units of measurement are converted into, and represented by ranks for integration in BN assessments. For the BN assessment ranks are assigned scores along a percentage continuum representing the state of the variables using natural breaks of 0.25 (zero), 0.5 (low), 0.75 (moderate) and 1 (high) in the calculation.

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3.6 Step 6: Calculate risks

From the general inclusive conceptual models (step 4), with the principle of requisite simplicity, smaller social and ecological endpoint specific models that represent the system being assessed are unpacked and converted into Bayesian Network models (Figure 5) for analyses. These models can be analysed individually or integrated using a range of BN modelling tools, using nodes representing variables that share the same indicators and measures. Bayesian Networks are probabilistic modelling networks that graphically represent joint probability distributions over a set of statistical values (Pollino et al., 2007; Korb and Nicholson, 2010). They include parent or input nodes and child or conditional nodes with links that represent causal relationships between nodes combined by Conditional Probability Tables (CPTs) (Mccann et al., 2006; Landis et al. 2016;). Conditional Probability Tables describe conditional probabilities between the occurrence of states in the parent nodes and the resulting probabilities of states in the child nodes (Landis et al., 2016). The two PROBFLO case studies presented here made use of the Netica^{TM} BN software by Norsys Software (http://www.norsys.com/).

The BNs are initially used to evaluate the risk of anthropogenic/natural hazards to endpoints per risk region, for multiple temporal periods (high or low flow months and wet or drought phases etc.), using available data and expert solicitations which represents risks to a current or present scenario. Present projections of risk to the endpoints can generally easily be validated using available data, knowledge of existing relationships between variables and by carrying out directed field survey campaigns to describe/test risk relationships. Present risk projections are then calibrated by evaluating benchmark or historical scenario risk projections using the established models, which can often be validated with historical data. These models are then used to determine E-flow requirements according to acceptable trade-off of risk to endpoints selected for the study, and the consequences of alternative water resource use, management and or climatic condition scenarios.

To determine E-flow requirements in PROBFLO, trade-offs of acceptable risk to social and ecological endpoints are initially established for each risk region by stakeholders, usually within a legislative context. These trade-offs of acceptable risk are represented in the BNs as forced endpoint risk distributions or profiles. These profiles usually range between low and moderate risk with usually no high risk probabilities. In relation to the definitions of the ranks used in PROBFLO, trade-offs of acceptable risk for E-flow determination should only dominate the “moderate” risk range when there is certainty that the E-flow requirements can be provided, such as in the case of E-flow releases from a dam. In case studies where there is high uncertainty associated with the ability to provide E-flow requirements, such as the management of multiple water resource users to cumulatively maintain E-flows, then a buffer should be provided according to the definition of ranks and the “low” risk range should be selected. After the selection of trade-offs of acceptable risk are established the calibrated BNs are forced to generate the state (rank distributions) of input flow variables used in the assessments. These flow related variable state requirements

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that are spatially and temporally referenced are provided to a hydrologist or geomorphologist for example to describe the E-flow requirements which can be presented in various formats, such as daily or monthly water (usually m3.$^{s-1}$) and sediment (usually kg.s.$^{m\wedge 3-1}$) discharge percentiles. During E-flow determination procedures the state of non-flow variable nodes, which contribute to the risk to endpoints, associated with flow variables can either be maintained in their current state, and described as such or amended with available water resource use information. This can include the increased requirement of water for Basic Human Needs, for increases in growths of human populations depending on the resource for example. Following the establishment of E-flows, the socio-ecological consequences of altered flows, associated with alternative water resource management options or climate change variability for example, can be evaluated in a relative manner by generating and evaluating a range of future scenarios in PROBFLO.

Senqu River risk calculation

In the Lesotho case study the nine social endpoints and three ecological endpoints were used in the assessment. These endpoints were used to represent the social-ecological endpoints of interest in the study. The 12 BN models established for the study included cause and effect linkages used to estimate risk. These BNs were used to evaluate the risk of multiple sources and stressors with flow related stressors for base winter (low), summer (high) and drought flows. Where appropriate CPTs of the BNs for endpoints were amended between RRs to represent the subtle changes in ecosystem process dynamics down the length of the Senqu River.

Data used in the case study was derived from a series of bio-physical surveys of the study area which sought to illustrate the hypothesised causal relationships from the BN models. Data obtained from the surveys, historical information and specialist elicitations were used to establish CPTs and describe input node rank thresholds. Risk ranking definitions and justifications for indicators and measures of each input node and the CPTs are available in the technical report of the study (LHDA, 2016). Real data and modelled hydrological statistics were used to evaluate the current risk to endpoints using Netica™. The tool is versatile and incorporates a range of features used to optimise the assessment. This includes equation features to weight the relative importance of parent variables and generate initial CPTs that were easily refined and applied to the daughter nodes for the assessment. The tool includes case file generation options which allows the BNs to be linked to Microsoft® Excel where data can be rapidly analysed and used to populate BNs for the analyses. Risk outcome distributions were also linked to Excel where scenarios and social and ecological endpoints could be integrated using Monte Carlo randomisation approaches that are part of the Oracle Crystal Ball software (Landis, 2004b). After establishing BN models for each RR, then input parameters were changed using RR specific data for a range of scenarios including:

- Scenario 1 represents the present day scenario based on present state hydrology, and associated source to endpoint variable state relationships that represent observable conditions. This scenario is based on existing data and additional data collected during the field surveys.

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- Scenario 2 represents a pre-anthropogenic water resource development scenario, considered to represent "natural" hydrology which was modelled using historical and modelled hydrology and rainfall data, and hypothesised state distributions for non-flow variables. This scenario was selected to calibrate the PROBFLO model for the study.
- Scenario 3 includes the presence of the new proposed Polihali Dam with full modelled Inter-basin Transfer (IBT) supply. Only large floods overtopping the dam have been considered to be available downstream of the dam with the existing E-Flows from the downstream lateral tributaries bringing water from Katse and Mohale Dams available in RR3 and 4. Non-flow source/stressor catchment conditions were based on the present day scenario.
- Scenario 4 is based on scenario 3 but includes E-Flow releases established as 36% of the natural Mean Annual Runoff (MAR), from the Polihali Dam, with suitable freshet and flood flows.
- Scenario 5 based on scenario 3 with only 25% of the natural MAR available to contribute towards E-flows with all floods retained in the Polihali Dam for transfer into the IBT.
- Scenario 6 is based on scenario 5 with one additional $40 m^3.s^{-1}$ freshet (small spring flood) released from the dam in addition to the 25% of the natural MAR to contribute towards E-flows.
- Scenario 7 based on scenario 3 with only 18% of the natural MAR available to contribute towards E-flows with one single $40 m^3.s^{-1}$ freshet (small spring flood).
- Scenario 8 is based on scenario 6 but with additional stress imposed by further reduction of available flows to 12% of the natural MAR, released for maintenance but including the single $40 m^3.s^{-1}$ freshet (small spring flood).

In this assessment risk was calculated for 12 endpoints, for three temporal periods, for eight scenarios, thus representing 312 BN models that were relatively comparable. The results include the mean relative risk rank scores with associated standard deviation for each endpoint including: maintain riparian vegetation, macro-invertebrates and fish wellbeing as ecological endpoints and maintain wood for fuel, marginal vegetation for livestock grazing and fish for food as social endpoints (Figure 6 and Figure 7). These initial relative mean risk scores allow for the comparison of alternative spatial and temporal socio-ecological risk projections to the endpoints used in the assessment. Initial risk to ecological endpoints compared between the natural (SC2) and present (SC1) scenarios, demonstrate that the number of sources and stressors with associated risk to endpoints has increased in the study area particularly in RR2 to RR4. These changes can largely be attributed to the consequences of Phase I of the LHWP (Figure 6). These findings include the synergistic effect of non-flow stressors (such as water quality and habitat condition) to the wellbeing of the Senqu River ecosystem in the study area. Effects of the altered hydrology between natural and present day scenarios to the social endpoints were less obvious (Figure 7). Spatial trends in the risk results associated with SC3 to SC8 generally include elevated risk to RR1, directly downstream of the proposed dam in particular. These results demonstrate that the impact on socio-ecological endpoints considered will be highest directly below the dam. Thereafter scenarios that exclude floods and freshets (SC3 and SC5) resulted in excessive risk demonstrating the importance of flood and freshet flows to the socio-ecological endpoints. Outcomes for scenarios 6 to 7 for riparian vegetation and invertebrates include consistent increases in risk spatially from the proposed new dam towards the lower reaches of the study area, which is ascribed to accumulative effects of the existing Phase I dams on the lateral tributaries. The relative risk to the fish community endpoint includes an opposite trend where a reduction in risk from RR1 to RR4 was observed for all scenarios. These results are indicative of the increased relative resilience of the resident and seasonal migratory fish communities to flow alterations in the Senqu River associated with dam developments, due to the increasing size of the river and associated increases in habitat diversity towards the lower reaches of the study area. In addition, reductions in river connectivity (barrier formation) associated with existing impacts from Phase I and the synergistic new stressors associated with Phase II of the LHWP was also shown to contribute to the increase in risk from the lower reaches of the study area in RR4 for fishes migrating upstream to RR1. Interestingly the outcomes included some improvements or reductions in risk to social endpoints for scenarios 6 to 8 in particular for; wood for fuel in RR2 and grazing for livestock for RR1 and RR4. These outcomes suggest that, based on our current understanding of the socio-ecological systems of the study area, some spatial trade-offs between some ecosystem services are available for stakeholders of the development to consider (Figure 7). These results describe the relative risk of altered flows to multiple endpoints in the context of exacerbating of non-flow variable conditions.

The cumulative risk of all ecological and social endpoints for each RR, for each temporal period, per scenario, were evaluated using Monte Carlo simulations (5000 trials, Oracle Crystal Ball software, Oregon) (Ayre et al., 2014). The outcomes included relative risk projections displayed as relative profiles to single endpoints from multiple RRs, and multiple social and ecological or all endpoints per RR in the study for comparisons and evaluation. These profiles were generated for multiple scenarios to evaluate the potential social and ecological consequences of alternative water resource development scenarios. This is demonstrated by considering the cumulative risk projections to the fish wellbeing endpoint, which demonstrates that relative to the “Natural” hydrology scenario (Scenario 2) where there is a 83% probability that risk to the fish endpoint occurred in a zero to low risk range, for the Present scenario (Scenario 1), Phase II with the dam and no E-flows scenario (Scenario 3) and Scenario 7 (Phase II with the dam, 18% release of natural MAR and $40m^3.s^{-1}$ freshets), all range between the moderate and high risk range (Figure 8). The risk outcomes of all future management options suggest that objectives of the stakeholders to maintain the existing wellbeing of the ecosystem could not be achieved with existing fish migration barriers that could not be mitigated with any of the alternative flow scenarios. An additional, amended scenario (Scenario 7) was then modelled which included successful mitigation measures for the existing man-made barriers in the Senqu River as amendments. The outcomes included a reduction in risk in the low to moderate risk ranges, demonstrating that scenarios that promote moderate to high use of the water resources, with barrier mitigation measures (such as construction of fish-ways) could result in the achievement of the fish wellbeing endpoints in the study. This approach established for this case study allows for the relative comparison of the integrated social and or ecological consequences of altered flows in the context of non-flow variables for each scenario for each endpoint used to represent the use and protection management objectives of the study as shown in Figure 9. In Figure 9 the integrated risk probability profiles to all endpoints for each RR which compares Scenario 2 (reference scenario) to the high use Scenario 3. These results include elevated risk probabilities for RR1 (84% moderate and 15% high rank range) and RR2 (81% moderate) while existing E-flows from Phase I dams reduce the risk posed for this scenario in RR3 and RR4. The relative risk results to endpoints and integrated risk profiles were presented to stakeholders who used these outcomes to select E-flows and associated water resource use mitigation measures (such as barrier mitigation measures) to be implemented for Phase II of the LHWP.

Mara River risk calculation

In the Mara River case study the relative risk of stressors and the E-flows were established according to the four social and two ecological endpoints considered in the assessment. The Mara River case study was based on existing data from historical surveys (Mati et al., 2008; McCartney, 2010; Majule, 2010; LVBC and WWF-ESARPO, 2010; Mango et al., 2011; Kanga et al., 2011; Defersha and Melesse, 2012; Defersha et al., 2012; Dutton et al., 2013; Atisa et al., 2014; Gichana et al., 2014; Kilonzo et al., 2014; McClain et al., 2014) and a single site visit by the author to refine the CPTs (NBI, 2016). During this survey seven sites were selected to represent the variability of the all of the RRs in the study area. After establishing BN models for each RR, input parameters were changed using RR specific data for two scenarios including the present condition and alternately the E-flow requirement to achieve the basic human needs and ecological wellbeing of the Mara River known as the Ecological Reserve (United Republic of Tanzania, 2009; Government of Kenya, 2002).

In this case study relative risk results were used to generate E-flow requirements that would not pose excessive risk to the wellbeing of ecological endpoints and social endpoints as described by the RQOs" (LVBC and WWF-ESARPO, 2010). In this case study, risk to the endpoints demonstrated that available flows currently exceed resource use demand, which means that additional flows could be allocated for use without compromising existing ecological endpoints. Results further demonstrate that sustainable water allocations would reduce risk to selected social endpoints considered in the study and meet the desired balance between the use and protection of the resource. The approach highlighted the probable effect of non-flow related stressors that are affecting the ecological wellbeing of Mara River, including water physio-chemical impacts and habitat alteration stressors associated with urban and rural communities, livestock grazing and watering and the effect of the recent exponential increase in local *Hippopotamus amphibius* populations in the tributaries of the Mara River in particular that are affecting water quality in the system (Kanga et al., 2011). These results were used to demonstrate the relative risk of flow reduction sources and non-flow reduction sources of risk to ecosystem wellbeing (Figure 10). The approach successfully demonstrated how the BN-RRM approach in PROBFLO can be used to generate acceptable risk profiles for endpoints to evaluate the socio-ecological consequences of altered flows. And how these models can be used to determine E-flows and associated information for water resource use.

3.7 Step 7: Uncertainty evaluation

Best ecological risk assessment practice requires the explicit evaluation of uncertainty, or confidence assessment, (O'Brien and Wepener 2012; Landis, 2004b), which has been incorporated into the PROBFLO approach. Any and all aspects of uncertainty associated with the entire BN-RRM process, including objectives and endpoint selection for the assessment, availability and use of evidence, expert solicitations and model uncertainty for example, must be addressed. In an effort to reduce uncertainty, the BN-RRM approach adopted by PROBFLO inherently considers uncertainty associated with cause and effect relationships and the use of real data with expert solicitations (Uusitalo, 2006; Landis et al., 2016). The additional incorporation of entropy reduction analysis in relative risk calculations using Monte Carlo simulations also contributes to uncertainty reduction in PROBFLO. Additional analyses of the sensitivity of the BN-RRM should be addressed within the uncertainty evaluation section (Pollino et al., 2007; Hines and Landis, 2014), where the relative influence of input nodes on the endpoints can be evaluated as part of the PROBFLO assessment. The results of the uncertainty assessment are used to provide context to the stakeholders of a PROBFLO assessment and contribute to the decision making process in E-flow assessment studies.

For all of the BNs created in the PROBFLO assessments of the Senqu and Mara River case studies, the sensitivity of the input variables were evaluated in Netica using the "Sensitivity to Findings" tool (Marcot, 2012). This approach allows for the relative contribution of each variable to be evaluated. These assessments are used to evaluate model structure and interpret risk result outcomes with the stakeholders of the assessment (Marcot, 2012; Landis et al., 2016). Additional sources of uncertainty include the comparative availability of evidence and expert knowledge pertaining to the socio-ecological systems considered in the assessments. The Senqu River case study addressed the second phase of a water resource use development that already has two substantial flow altering developments with more than 15 years of pre and post-development E-flow assessment (using holistic EFA methods, (Arthington et al., 2003)) monitoring and evaluations. Additional field surveys to the study area were carried out to generate additional information and test existing hypotheses for the assessment. The Mara River case study was based largely on available historical information and existing EFA results for parts of the study area (McClain & Kashaigili, 2013; Dessu et al., 2014). To further reduce uncertainty associated with the application of the PROBFLO assessments, the BN-RRM method proposes an adaptive management approach (Step 8) that allows improvements over time as new data is collected.

3.8 Step 8: Hypotheses establishment

In the hypotheses establishment step of PROBFLO, suitable hypotheses for field and laboratory experiments are established to test flow-ecosystem and flow-ecosystem service relationships (Landis, 2004b; O'Brien and Wepener, 2012). In PROBFLO the fundamental adaptive management approach to improving our understanding of socio-ecological risk relationships, while revisiting outcomes and re-evaluating approaches is formalised in the hypotheses establishment and testing phase. This process is based on a similar process in the RRM approach, established to reduce uncertainties and to confirm the risk rankings in risk assessments (Landis, 2004b). In PROBFLO these adaptive management principles acknowledge that socio-ecological systems are dynamic and that our limited understanding of these processes necessitates the incorporation of many assumptions. In many case studies, uncertainties associated with the outcomes need to be mitigated before they can be used to inform decision making. To reduce uncertainty, assumptions can be tested rigorously and early. The adaptive management processes should be (1) informed by iterative learning about the flow-ecosystem and flow-ecosystem service relationships, (2) consider and respond to earlier management successes and failures and (3) increase present day socio-ecological system resilience that can improve the ability of E-flows management to respond to the threats of increasing resource use (Lee, 2004).

In the Senqu River case study, many hypotheses associated with the flow-ecosystem and flow-ecosystem service relationships, largely established on data associated with Phase I of the LHWP, were established and tested during the field surveys. These hypotheses included (1) woody vegetation communities sustainably harvested by local communities for fuel, respond to reduced average flows by increasing in abundance due to reduced flow variability, reduced stream power and through the colonisation of new lower marginal zones , (2) migratory cyprinid fishes respond to ecological cue flows that include increased discharges associated with reduced salinity, that initiates fish migration and (3) grazing for livestock of local communities depends on freshet flows lifting water onto the river banks and floodplains to stimulate vegetation growth. Data was collected from the study area to address these hypotheses and improve on the understanding of the flow-ecosystem and flow-ecosystem service relationships considered in the study. In the Mara River case study available flow-ecosystem and flow-ecosystem service information was used in the PROBFLO assessment. A range of hypotheses associated with our understanding of the relationships were generated to refine and improve on E-flow assessments of the study area.

3.9 Step 9: Test hypotheses

The two PROBFLO case studies included the design of long-term monitoring programmes to test the accuracy of risk projections and improve the understanding of the flow-ecosystem and flow-ecosystem service relationships. In the Senqu River case study a data management system (DMS) with automated data evaluation components was established. In the Mara River case study a range of hypotheses were established and used to design a monitoring plan and associated research programme to confirm the flow-ecosystem and flow-ecosystem service relationships considered in the study.

3.10 Step 10: Communicate outcomes

The RRM approach highlights the importance of clear and careful communication of the outcomes in the context of the uncertainty identified in an assessment (Hayes and Landis, 2004), which approach is adopted by PROBFLO. A variety of

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techniques and tools are available to assist in the communication of the E-flow outcomes and associated socio-ecological consequences of altered flows and careful attention must be paid to ensure that the relevant stakeholders of any case study are presented with information that can easily be understood (O'Brien and Wepener, 2012).

4. Conclusion

The Regional Scale Ecological Risk Assessment approach was established in 1997 in response to the need to apply ERAs on multiple spatial scales, and include multiple sources, stressors and receptors in considerations of spatial and temporal ecosystem dynamics (Landis and Wiegers, 1997; 2007). The approach, which includes the RRM, has been widely implemented, reviewed and proven to be a robust probabilistic modelling tool to contribute to the sustainable management of ecological resources (Landis and Wiegers 2007). Recent developments in E-flow frameworks (Poff et al., 2010; NBI, 2016), now also call for holistic, regional scale, probabilistic E-flow assessments that consider flow and non-flow drivers of change in socio-ecological context. The BN-RRM approach incorporated into this regional scale E-flow assessment method we've called PROBFLO, similarly offers a robust approach to E-flow assessments that can make a positive contribution to the sustainable management of water resources. The approach provides true transparency and adaptability options for holistic E-flow management. PROBFLO has already been implemented in two major case studies where its flexibility and functionality has been demonstrated. In both case studies the evidence based outcomes facilitated informed environmental management decision making, in the context of social and ecological aspirations. From these outcomes stakeholders have in addition, been able to consider sustainable social and ecological trade-offs between, to balance the use and protection of water resources. Although the accuracy of the PROBFLO projections used to guide sustainable water resource use needs to be validated when developments takes place, the adaptability of the approach allows for the incorporation of new information rapidly which will inform adaptive management. The approach is being established within adaptive management processes of existing case studies, and applied in new case studies for a wide range of water resources with diverse social and ecological objectives.

Author contribution

The BN-RRM approach established for use in E-flow assessments was co-developed by G.C. O'Brien, C. Dickens and V. Wepener. The approach was implemented by this team including E. Hines and R. Stassen. The paper was written by G.C. O'Brien and C. Dickens and edited by W.G Landis, V. Wepener, E. Hines and R. Stassen.

Competing interests:

The authors declare that they have no conflict of interest.

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FIGURES

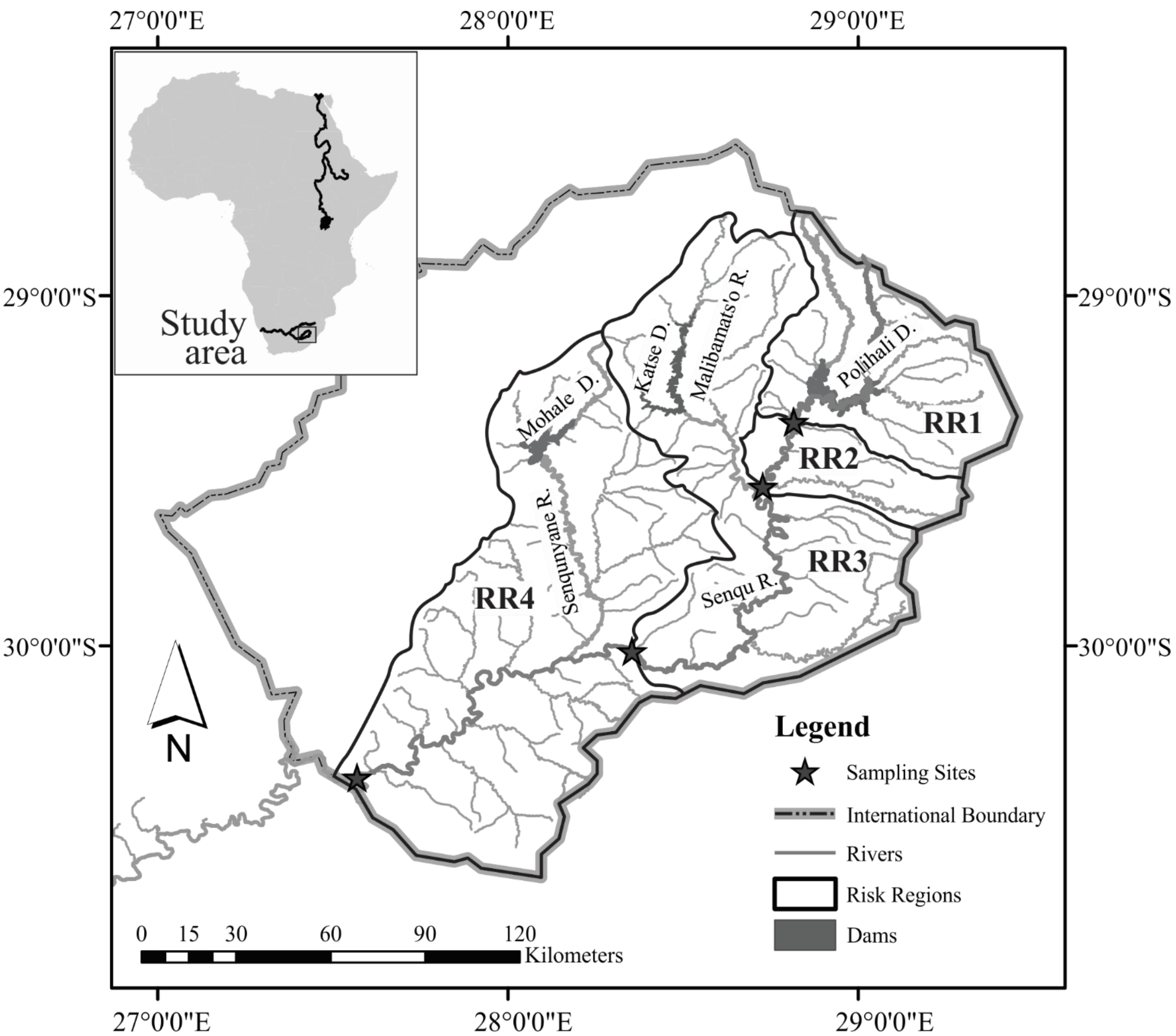

Figure 1: The upper Senqu River study area with Risk Regions established for the study including dams associated with Phase 1 of the Lesotho Highlands Water Project and the location of the new Polihali Dam planned to be built in Phase 2.

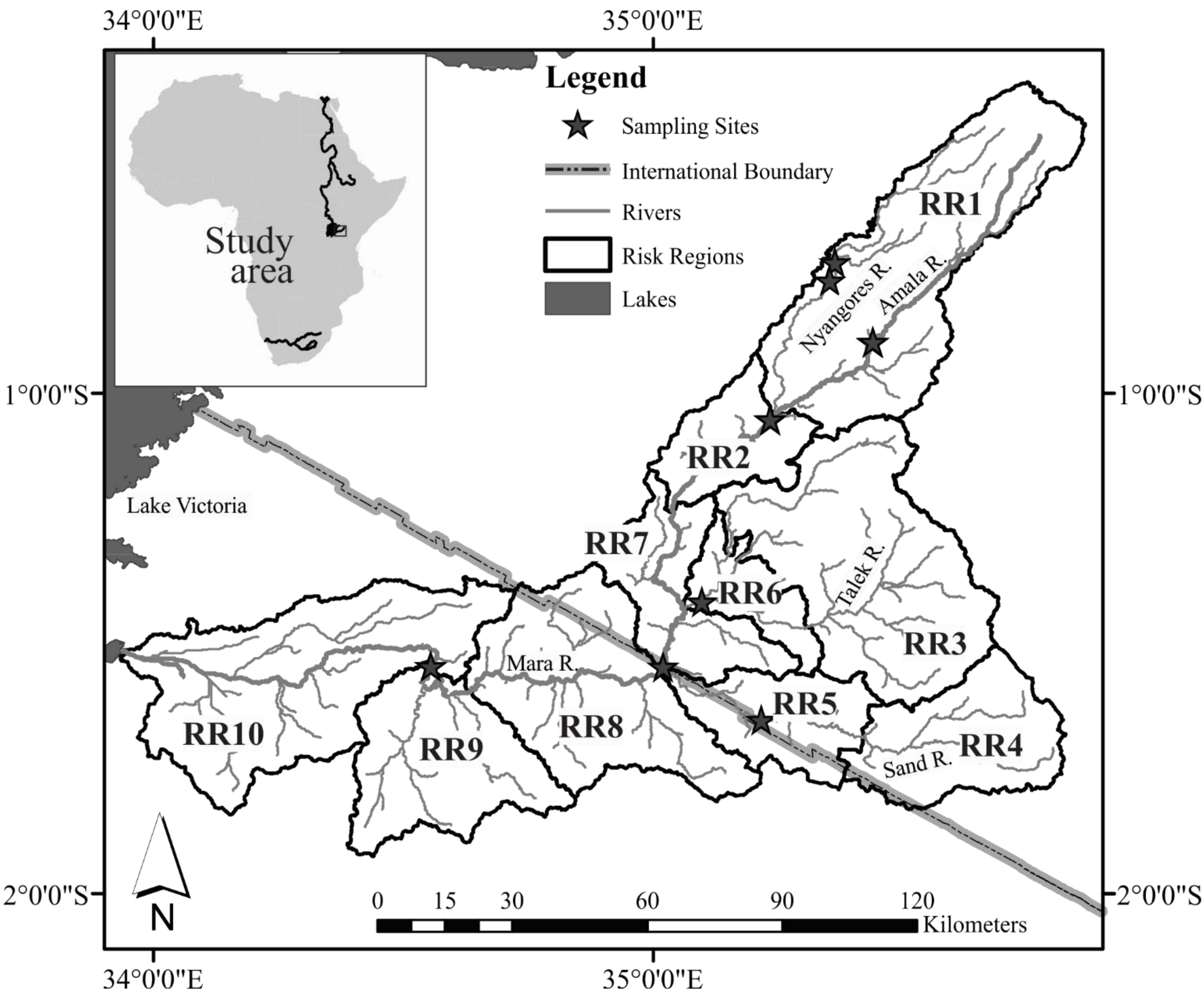

Figure 2: The Mara River Basin considered in the study with Risk Regions and sampling sites.

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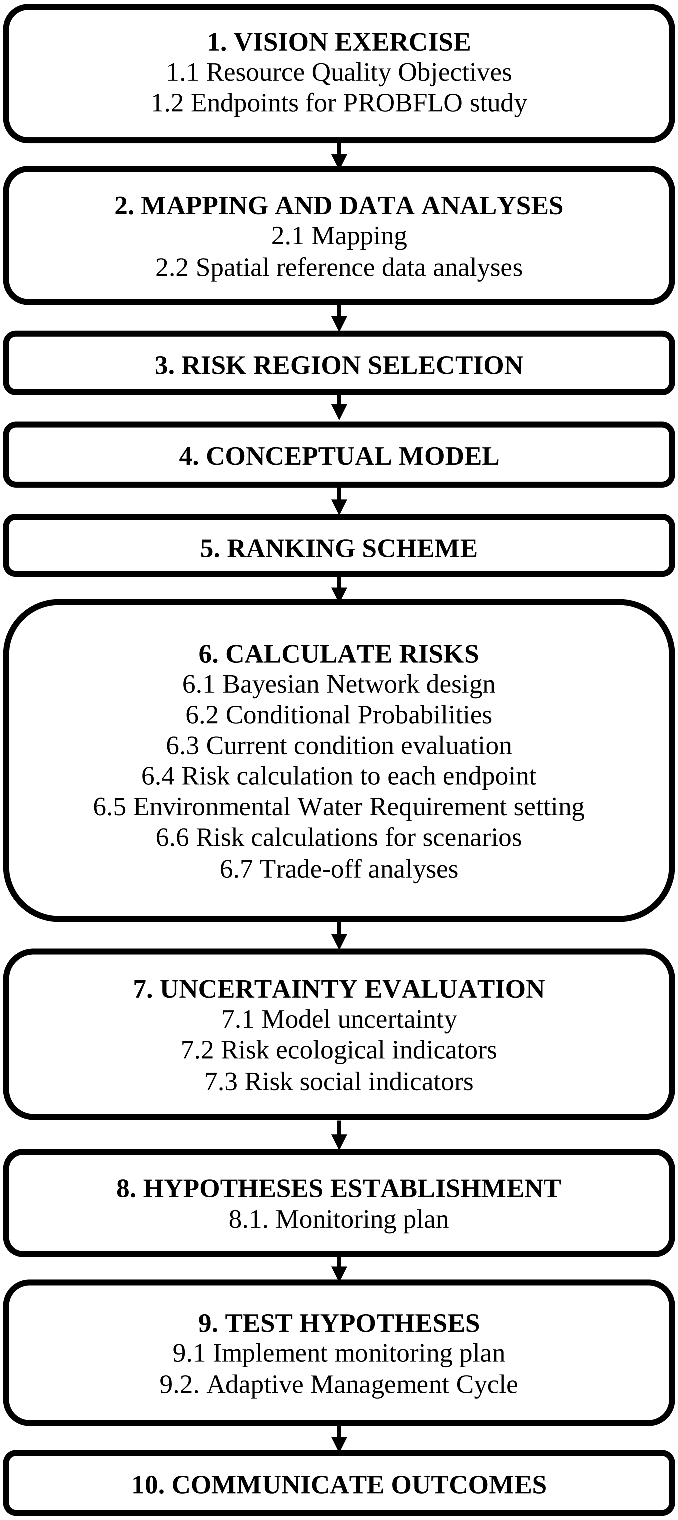

Figure 3: The ten procedural steps of PROBFLO.

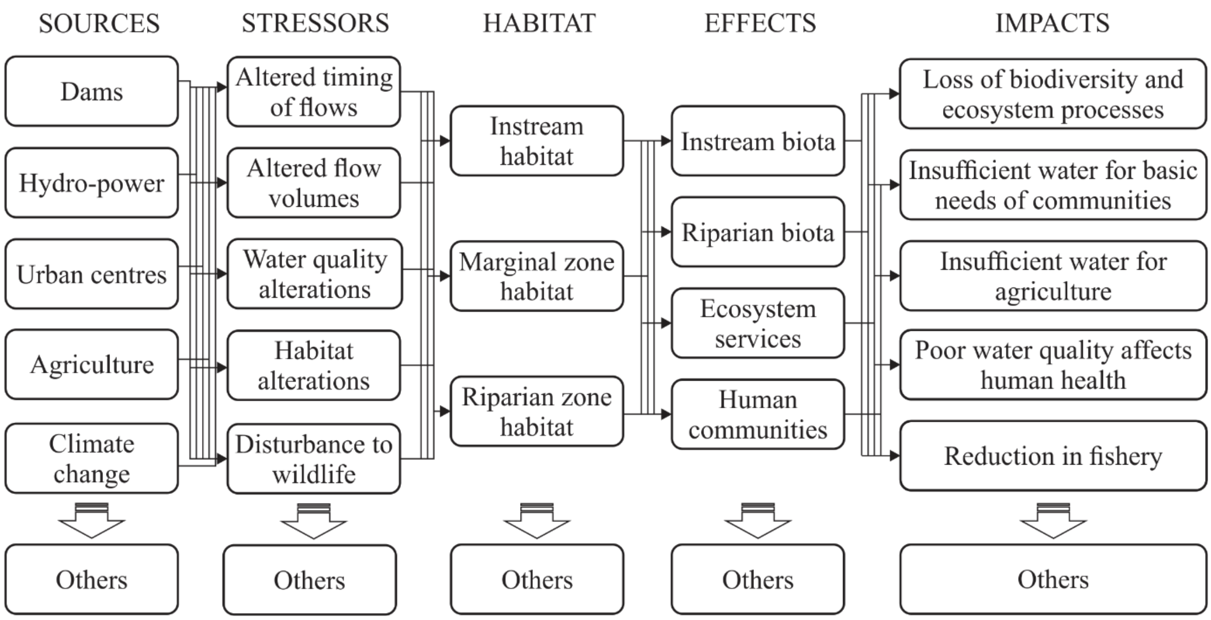

Figure 4: Example of a holistic conceptual model for PROBFLO which describes causal risk relationships between sources, stressors, habitats, effects and impacts to endpoint considered in an assessment.

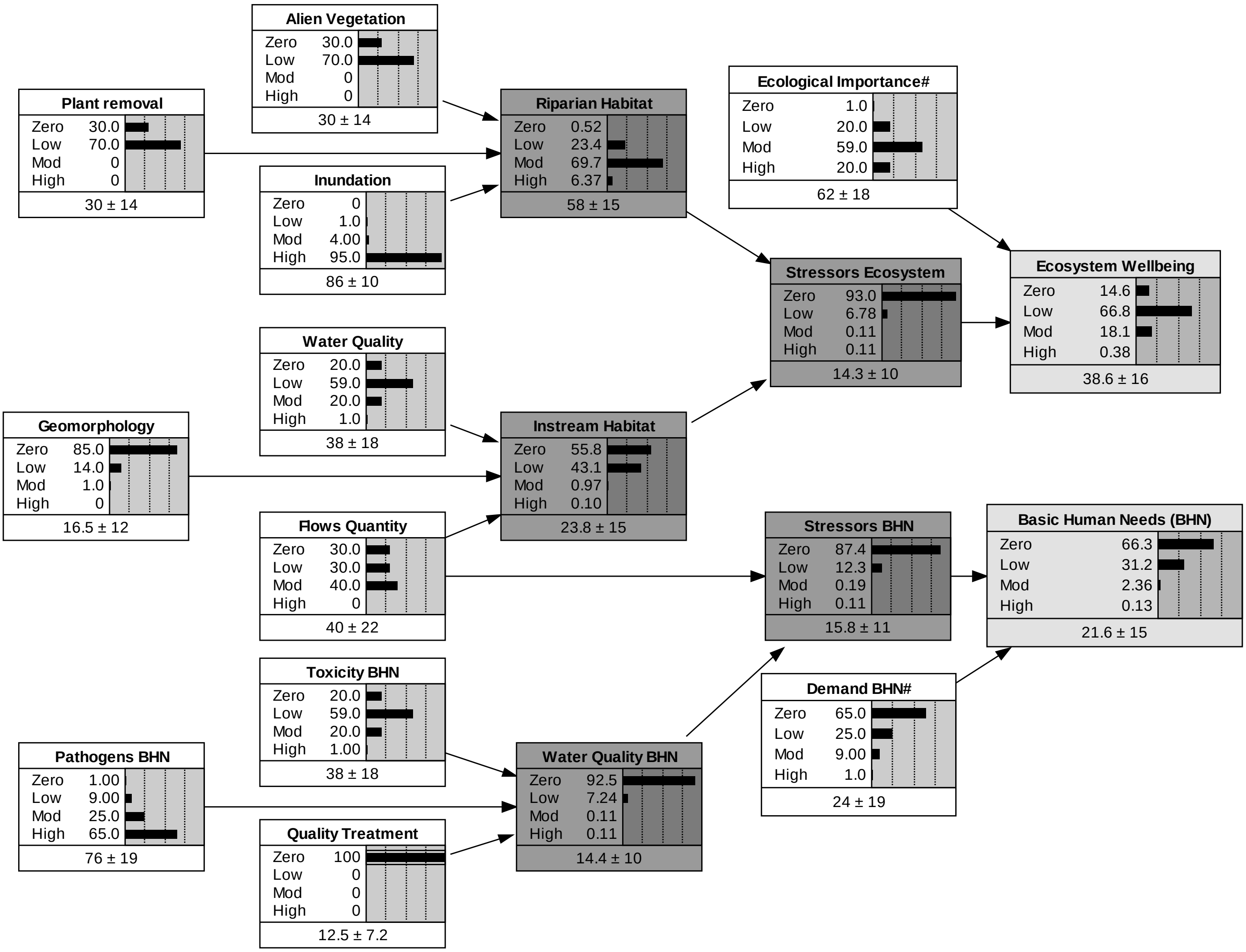

Figure 5: Example of a Bayesian Network model developed for a PROBFLO case study to evaluate the risk of water resource use to an Ecosystem Wellbeing and Basic Human Needs Endpoints. (*) Identifies flow variables which are included to establish E-flow requirements and evaluate the socio-ecological consequences of altered flows. White nodes represent input variables (# indicates effect nodes), dark grey nodes represent daughter/child nodes and light grey nodes represent endpoints.

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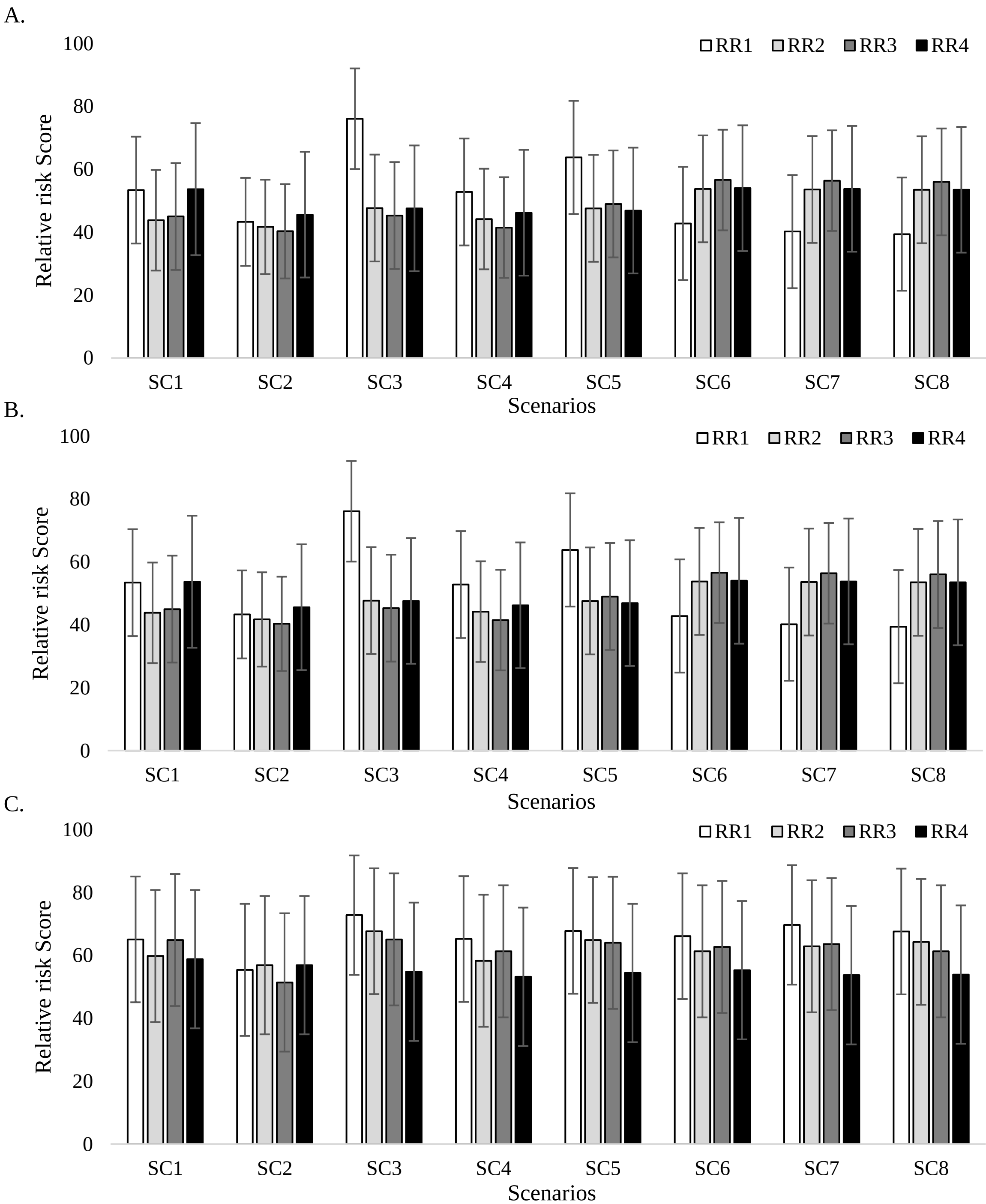

Figure 6: Senqu River mean relative risk scores (with SD) for the endpoints considered in the assessment including: riparian vegetation (A), macro-invertebrates (B) and fish (C) wellbeing endpoints for the four risk regions per scenario (SC).

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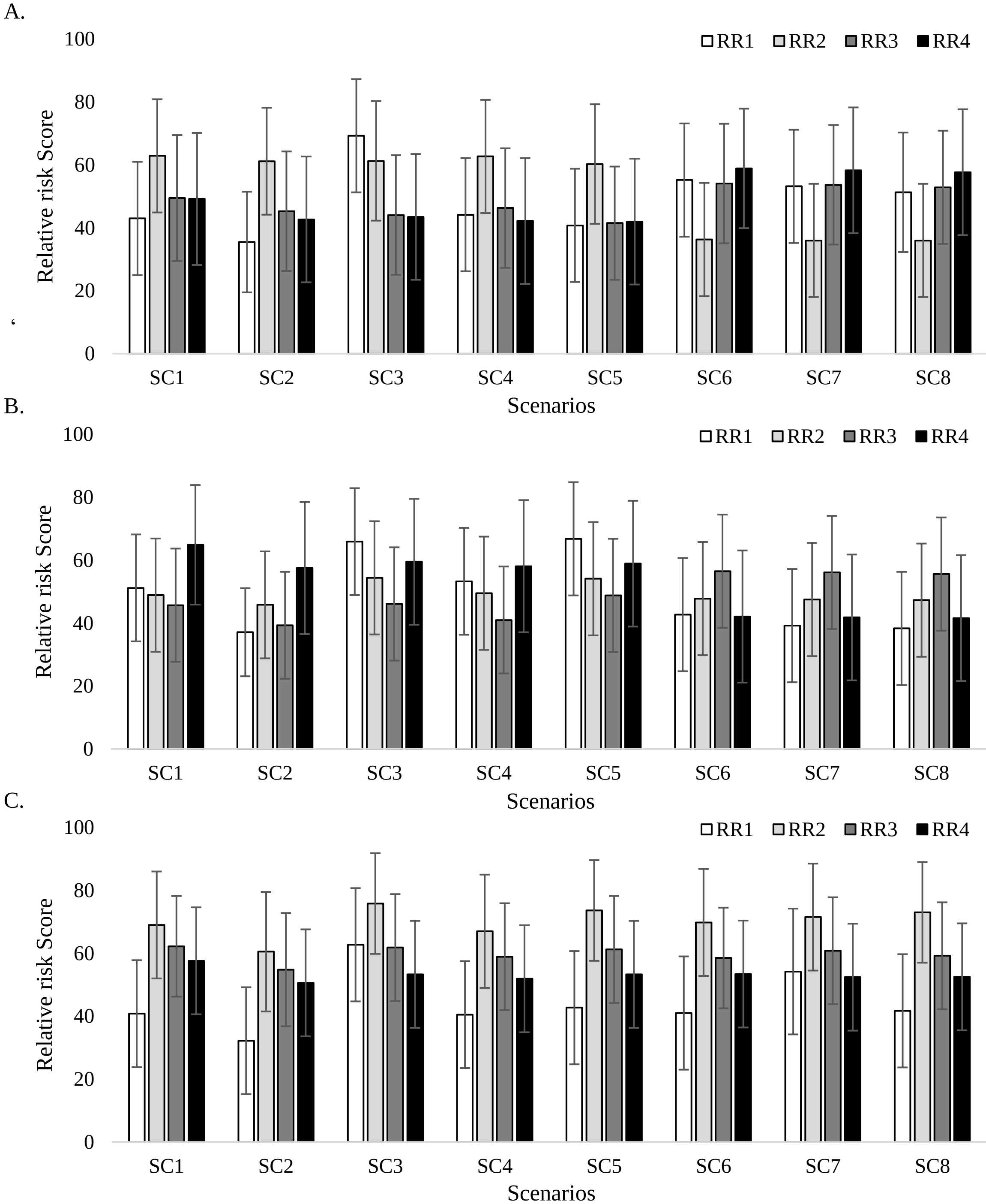

Figure 7: Senqu River mean relative risk scores (with SD) for wood for fuel (A), marginal vegetation for livestock grazing (B) and fish for food (C) social endpoints for the four risk regions per scenario (SC) considered in the study.

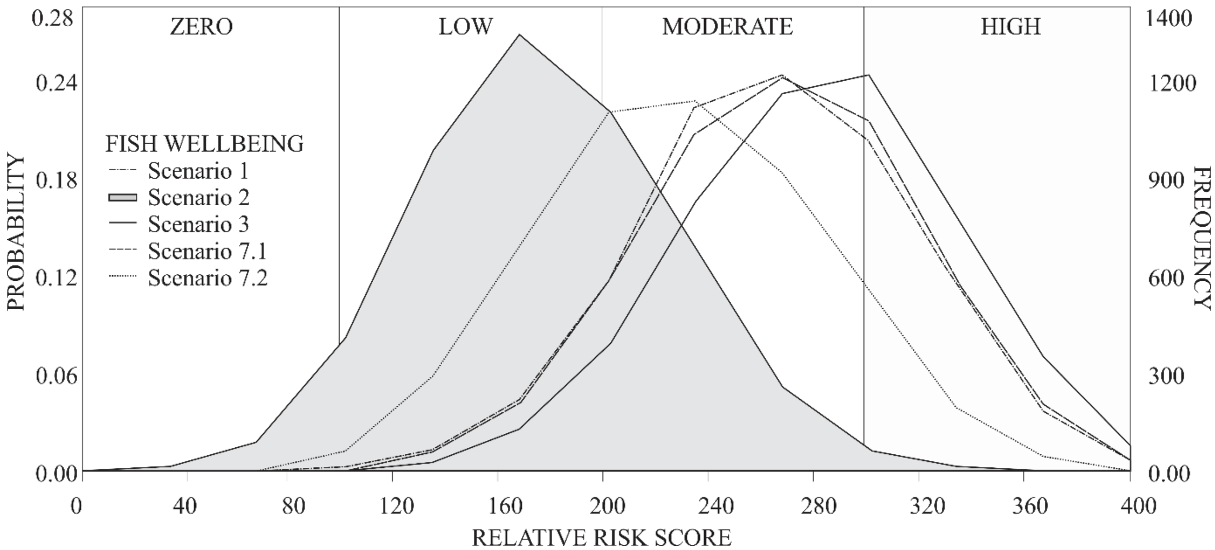

Figure 8: Probability profiles generated during a PROBFLO assessment to describe the relative risk of the multiple sources and stressors, including altered flows, associated with alternative management scenarios considered in the Lesotho case study to the fish wellbeing endpoint.

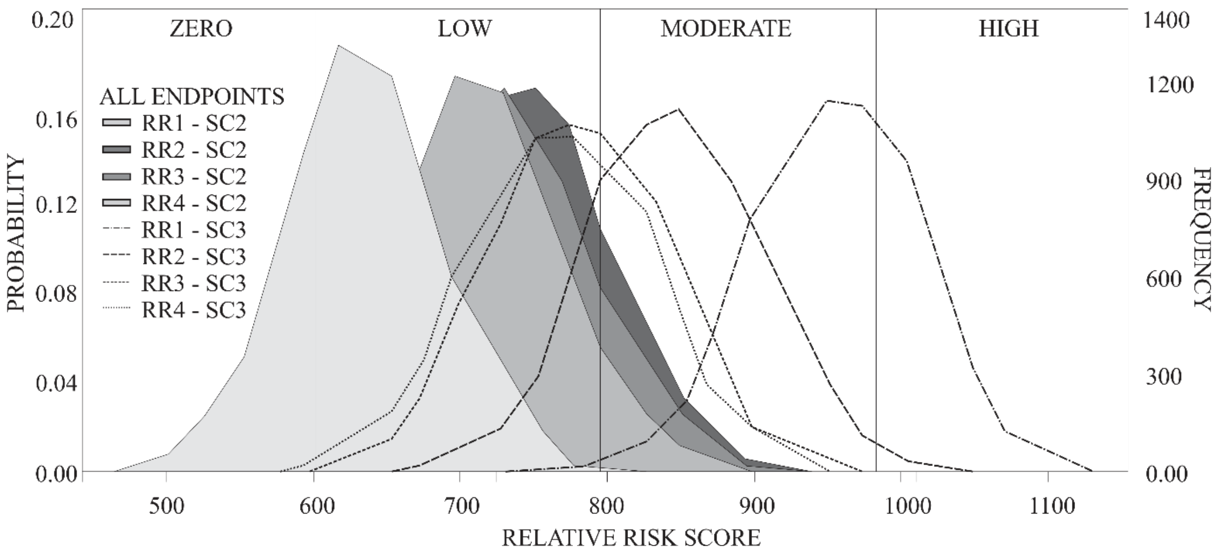

Figure 9: Probability profiles generated during a PROBFLO assessment to describe the relative risk of the multiple sources and stressors, including altered flows, associated with alternative management scenarios considered in the Lesotho case study to all of the endpoints integrated in the assessment.

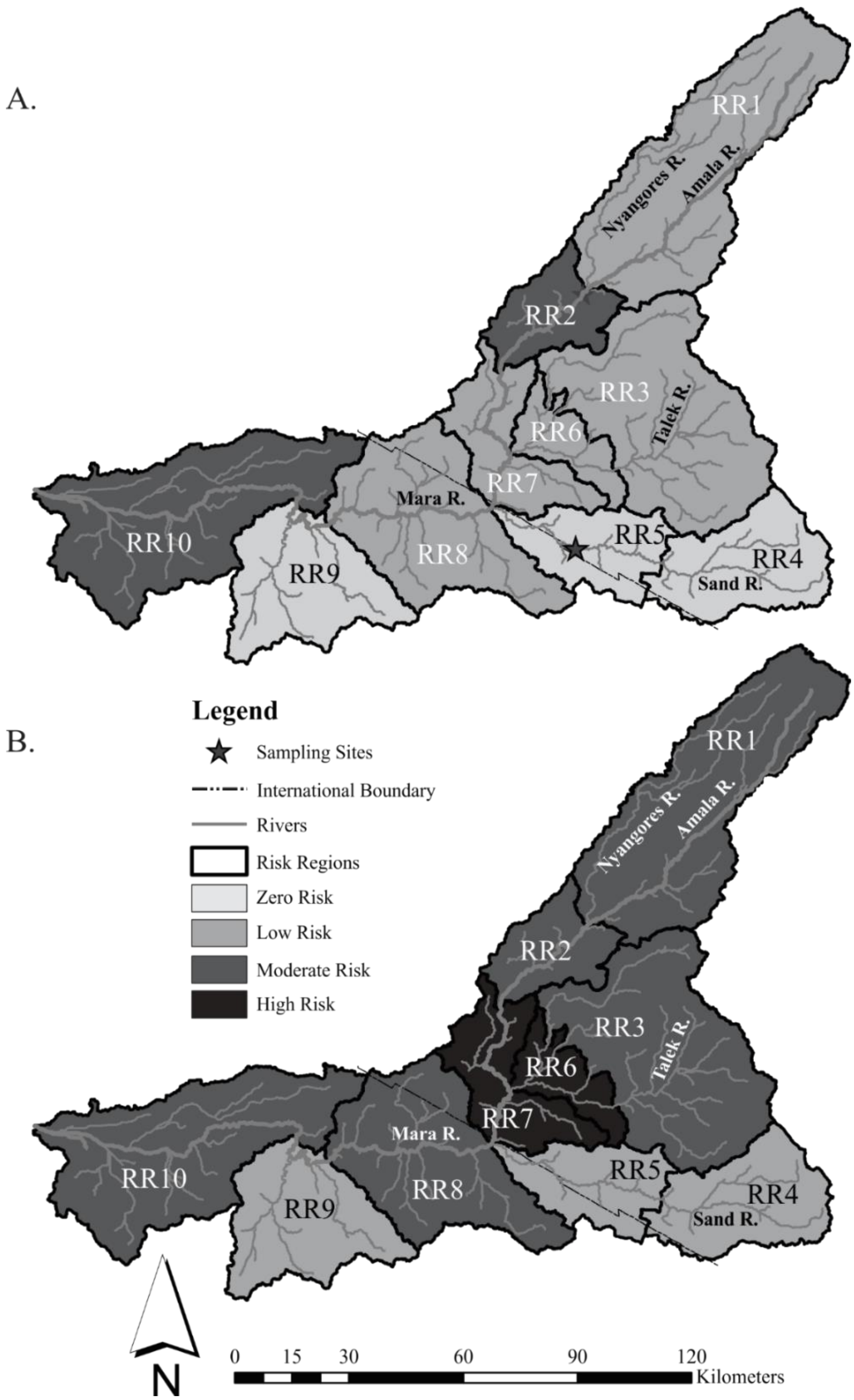

Figure 10: Relative spatial risk of the multiple sources and stressors associated with current (A) and planned (B) water resource use in the Mara River Basin.