TECHNICAL REPORT

Development of an Environmental Flow Implementation and Monitoring Tool: Enhancing the usability of the PROBFLO e-flows framework in the Limpopo Catchment

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ABSTRACT

This study presents an innovative tool and approach developed to facilitate the adaptive testing or monitoring of e-flow frameworks and environmental flows (e-flows) implementation using digital tools and real-time data to ensure sustainable water resource management. The project, conducted in two river basins in southern Africa, focuses on creating a user-friendly digital Application Tool, integrated with a high-resolution 3D model and modern sensors, to monitor changes in river ecosystems post e-flow implementation. The methodology, grounded in the established PROBFLO e-flow frameworks for these two basins, involves an eight-step process to determine e-flows for maintaining sustainable ecosystems and the holistic testing of the socio-ecological consequences of altered flow and non-flow environmental variables. It begins with site selection, considers physico-chemical dynamics, establishes flow-ecosystem relationships, and generates flow scenarios. Utilizing Bayesian Networks (BN), the model evaluates risk or socio-ecological consequences associated with proposed e-flow requirements and any other past, present or future resource development scenario, integrating ecosystem components to ensure the holistic suitability of the determined e-flows. The risk assessment builds on to the ecological components with the including of ecosystem service allowing for the social consequences of altered flows to be evaluated using the same framework. The development of a user-friendly PROBFLO Environmental Framework Assessment (EFA) Tool enables stakeholders to test scenarios and assess risk outcomes without extensive probability or resources specialization expertise. The PROBFLO EFA Tool streamlines data analysis and BN modelling, offering an accessible platform to evaluate e-flow scenarios. While the PROBFLO EFA Tool is still undergoing refinements, its potential to empower users in making informed decisions regarding e-flow management is evident.

1. Introduction

1.1. Background

Environmental flows (e-flows) represent the volume and quality of water that needs to remain in a river to sustain the ecosystem and hence all those who benefit from a functional ecosystem (thus, society and the economy) (Arthington, 2018). PROBFLO is an e-flow determination tool and framework with capabilities to model the holistic requirements of ecosystems that inform holistic e-flow determination and present the socio-ecological consequences or risk of altered flows on ecosystem services (Horne et al., 2017; O'Brien et al., 2018). Following the application of PROBFLO to determine e-flows and evaluate the socio-ecological consequences of altered flow scenarios (past, present, e-flows and a future climate change scenario) (O'Brien et al., 2022), the objective of this study is to support the implementation of e-flows around the world which has been poor despite a wide-spread acceptance of the philosophy, demonstrating this for the Limpopo and Incomati Basin. While

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monitoring e-flow volumes from a hydrological and water quality perspective is a relatively simple matter, monitoring the effectiveness of the prescribed e-flows and the socio-ecological response of e-flow provision requires evidence of a sustained ecosystem and associated condition of human communities. This project will investigate whether appropriate digital tools and real-time ecosystem monitoring data could assist with the management, education, awareness and implementation of e-flows. This project will include digital approaches to monitoring the change in river ecosystems following the implementation of e-flows in two river basins in southern Africa (Limpopo and Incomati), facilitating an adaptive management approach for sustainable water resources management globally.

1.2. PROBFLO

A PROBFLO Framework software application front-end tool is being developed to operationalize the Limpopo River PROBFLO Framework for use by stakeholders of the Limpopo River Basin e-flows, and to demonstrate the development of a PROBFLO E-flow Framework Application Tool (PROBFLO EFA Tool) for the international e-flow development, implementation and management community. This PROBFLO EFA tool provides stakeholders who are interested in established PROBFLO e-flow and socio-ecological consequences or risk assessment outputs (for example the Limpopo e-flow Framework https://limpopo-eflows.iwmi.org) with the opportunity to test existing, new modelled or observed river flows and use scenarios for any one of the studied sites. The PROBFLO EFA tool incorporates a simple frontend template where users can change water quantity (hydrology), water quality, or any other environmental driver state/condition (e.g. changes in dynamics of barriers or alien invasive species impacts). These new conditions represent a new scenario to be considered and are automatically applied to the existing e-flows framework models. The results of the risk assessment, representing probable risk or harm to selected socio-ecological endpoints, are automatically generated.

This innovation will allow PROBFLO to become a adaptive framework, as real future scenarios can be compared to model predictions from which the model can learn and update its understanding/representation of the socio-ecological system of interest. This will result in an improved ability of the model (PROBFLO Framework) to predict future socio-ecological consequence of altered flows, and other stressors by stakeholders automatically. Presently this can only be carried out by experienced e-flow scientists, so a new PROBFLO EFA Tool will increase the contribution stakeholders can make to sustainable water resources management.

PROBFLO was developed by O'Brien et al (2018) as a holistic e-flow assessment method that includes both the relative-risk model and Bayesian Network – Relative Risk Model (BN_RRM) into a probabilistic modelling tool that explicitly addresses uncertainty. PROBFLO evaluates the socio-ecological consequences of various water resource scenarios and generates e-flow requirements on a regional spatial scale. It follows the ecological risk assessment exposure and effects approach, with multiple stressors, habitats and ranked ecological impact relationships displayed in graphical Bayesian Network (BN) models that use conditional probability distributions to represent the relationship between the variables (O'Brien et al, 2018). For this case study the existing PROBFLO Framework for the Limpopo River (O'Brien et al., 2022) was used.

In the following section, a summary of the 8 steps of the PROBFLO approach to determine holistic e-flows required to maintain sustainable ecosystems in multiple reaches of a regional water resource is provided (Consider O'Brien et al., 2018; 2022).

Step 1: Identification and selection of sites

Step 1 is to identify and select site/s representative of a river reach (Figure 1). For this example, the Balule site on the Olifants River was selected. This site is located in the lower reaches of the Olifants River to represent the effects of altered flows in the upstream catchment. The criteria for site selection for the collection of data is normally based on biophysical characteristics, and includes representativeness of the reach considered, access to the site for bio-physical surveys, existing data especially hydrological, and local and regional land use or resource development scenarios. Data from the site is needed so that flow-ecosystem and non-flow stressor and ecosystem relationships can be determined. At this stage the vision for the river reach in terms of its protection vs. use/development must be considered.

Step 2: Consideration of the physico-chemical dynamics of the ecosystem

In Step 2 of the e-flow determination process the physico-chemical dynamics of the ecosystem for a holistic e-flow assessment are considered for each reach of river (Figure 2). Here available flow gauging data and rainfall information is used to establish hydrological statistics for the resource being evaluated. Statistics representing natural and present conditions including the durations, volumes, timing and frequencies of flow are determined. These statistics are summarized into different formats including flow exceedance tables that are foundational to scenario evaluations in PROBFLO.

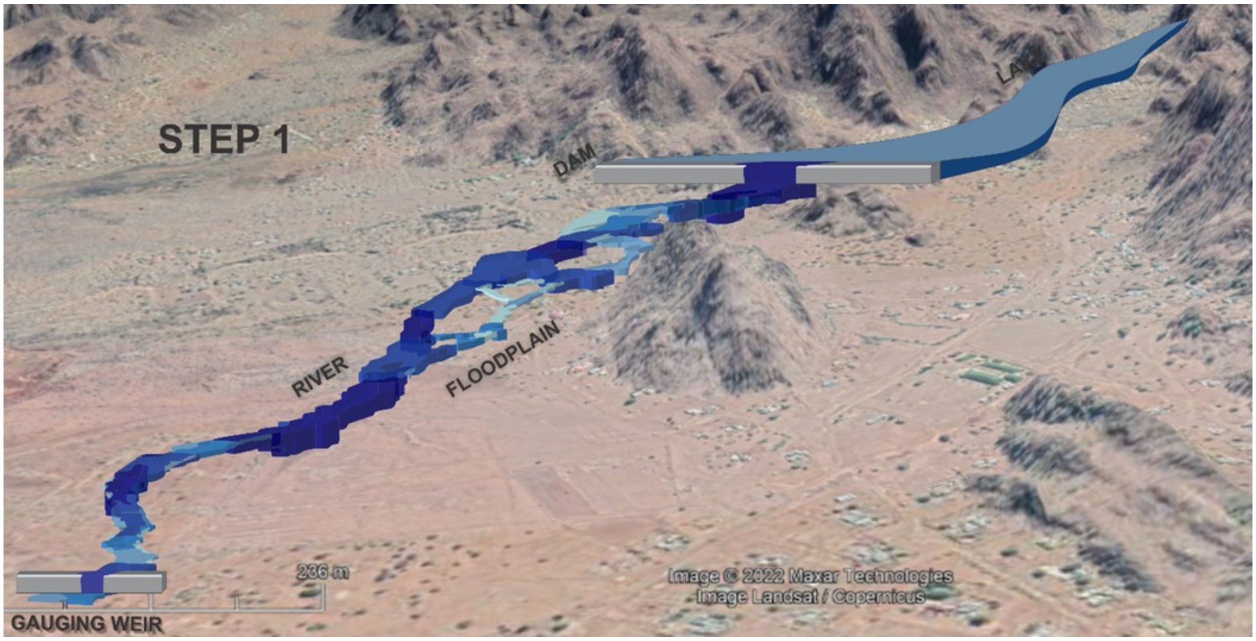


Figure 1. Step 1 of PROBFLO integrated e-flow determination approach. Identification of representative reach of the water resource in the landscape for e-flow determination.

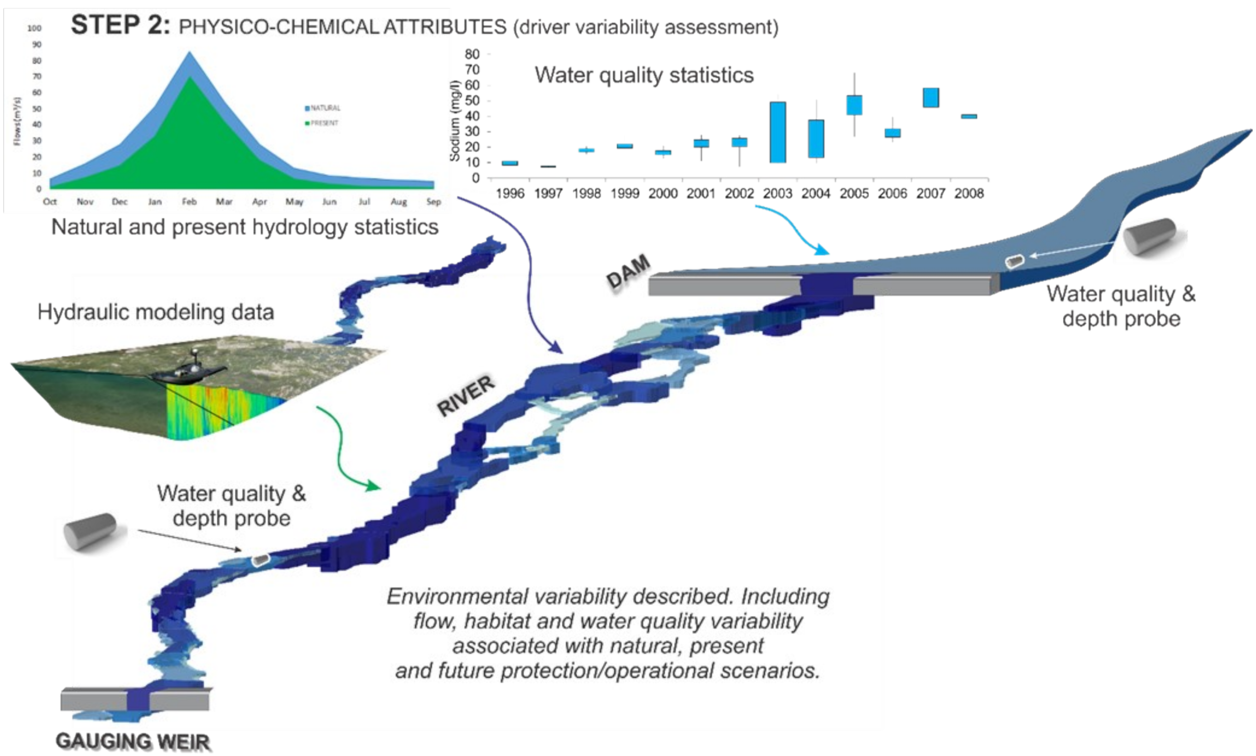


Figure 2. Steps 2 of PROBFLO integrated e-flow determination approach. Characterization of physico-chemical dynamics of ecosystem for holistic e-flow assessment associated with each reach of the system considered.

The flow dynamics of each river reach are described to represent the habitat dynamics which can be achieved through hydraulic modelling. In holistic e-flow determination assessments, at least a cross section (1d), or multiple cross sections (multiple 1d sections) or best of all, an integrated model at a reach scale (2d), are used for the hydraulic modelling. These models facilitate the evaluation of changes in flows as related to habitat characteristics including depths, levels, wetted area, velocities and turbulence of flow within the water column. Hydraulic models and associated hydro-dynamic or fluid-mechanics information is used to describe the availability and or condition of instream and riparian habitat/s through association with flow variability and geomorphological processes. These models can also be used to evaluate future habitat characteristics that could result from predicted e-flow scenarios.

Historical and natural water quality variability of the water resource being considered is also required as foundational information in an e-flow assessment. The data is usually based on available historical vs. present trends in the ionic concentrations of salt, nutrient and toxicants of interest in the study area due to natural geological features of the resource, including naturally high salinities and serpentine soils for example, and anthropogenic activities resulting in water quality stressors. In holistic e-flow determination studies the relationships between river flows and water quality constituents through for example dilution flows required to provide suitable ecosystem conditions is required. Summer freshet flows can also be considered to flush nuisance water quality constituents or maintain the quality of refuge pools in rivers during dry, low flow conditions. River flows also support groundwater recharge which in-turn will result in groundwater linked pools in rivers during dry periods or reduce ground water intrusion if the quality of that aquifer is undesirable. Groundwater flows contributing to baseflow or sustaining pools during the dry season are thus particularly important aspects. All this physico-chemical information is used to represent the physical dynamics of the habitats of a water resource being considered in an e-flow study.

Step 3: Determine flow-ecosystem relationships

With a good understanding of the habitat characteristics of a river reach, floodplain, lake and or estuarine resource being considered in a PROBFLO assessment, holistic flow-ecosystem relationships that characterise a sustainable ecosystem are determined in Step 3. Here a range of ecosystem lines of evidence (LoEs) are used to identify species, populations and community indicators that represent the ecosystem and their preferences for the volume, timing, duration and frequencies of flows. Fish, macroinvertebrates and aquatic and riparian vegetation were selected to represent the riverine ecosystems. Holistic e-flow assessments have previously established these ecosystem components as foundational components to consider in e-flow assessments. For specific case studies, amphibians, microbes and or regulator ecosystem services can be included in e-flow assessments to represent functioning sustainable ecosystems.

The application of these indicators results in a range of flow-ecosystem relationships which in the PROBFLO process are presented as rule or conditional probability tables. In order to represent the flow-ecosystem relationships graphically, the rule and conditional probability relationships are represented in stacked area charts that represent the ecological components as areas stacked in relation to discharge. The stacked area charts used to represent the relationships are cumulative areas and always represents 100%. These are divided into ranks that relate, for example, to ideal or pristine (synonymous with zero risk rank), sustainable or suitable (synonymous with low-risk rank), threshold of potential concern (synonymous with moderate-risk rank) and unsustainable or unsuitable conditions (synonymous with high-risk rank) in the graphs (see Figure 3).

The flow-ecosystem relationship data includes species, populations and community requirement/preference information for the volume, duration, frequency and timing (e.g. seasonality) of flows. In a PROBFLO assessment habitat depth and velocity requirements are generated to:

- maintain refuge areas for species,
- provide access for migration, spawning and recruitment,
- optimize water quality conditions of instream habitats, and
- optimize levels required to inundate cover features
- facilitate recruitment of indicator riparian plants.

Additional data pertaining to sediment flows, habitat conditions and the movement and deposition of sediments is considered. These relationships can also consider the timing and duration of flows to ensure that they are aligned to seasonal life-cycle activities of indicator species. With this evidence of the requirements or preferences of ecosystem indicators, and knowledge of the use or protection focus of the vision for the resource, multiple ecosystem requirements can be generated to contribute to the determination of e-flows. These indicator requirements often pertain to life-cycle processes of indicator species including for example the habitat for indicator species to spawn in, recruit from, grow in and or migrate between. These habitats associated with the timing of life-cycle attributes results in the volume, timing, duration, and frequency of flows to maintain these indicators.

For the e-flow determination, the state of the indicators is extracted to generate the flow requirements and the ranking scheme established for the study corresponds to the state of the indicators. If the vision for the resource is use focused the requirements associated with the moderate risk rank range is used while if the vision is protection focused, then the low rank range is usually considered to generate flow requirements for each indicator. In these assessments a range of requirements generated from indicator species, populations and communities is summarised to represent the drought, base low, base high, freshet and flood requirements for each site. The hydrologist thus obtains indicator requirements pertaining to the volume, timing, duration, and frequency of flows for each site associated with drought, base low and high flows, freshets and floods.

Step 4: Generation of flow scenarios

In Step 4 (see Figure 4) the information obtained in Step 3 is used as controls to generate a flow scenario that meets these isolated requirements provided. Consider however that these requirements are generated independently and only integrated by the hydrologist to represent an initial e-flow requirement. Consideration of the potential synergistic effects of altered flows and combinations of the independent requirements still needs to be considered. The PROBFLO approach is a holistic assessment that then considers the integrated requirements, or synergistic effects of the indictor e-flow requirements using the RRM and BN approach described now in Steps 5-8 (see Figure 5 to Figure 7).

Step 5: Evaluation of the integrated risk of preliminary e-flow requirements

In Step 5 (Figure 5) the knowledge of the socio-ecological system representing each reach of river in the case study and links between sites to represent upstream and downstream relationships is used to evaluate the integrated risk of preliminary e-flow requirements, to ensure that they meet the integrated ecosystem requirements. This is achieved using BN probabilistic modelling methods using the Norsys Netica tool. This holistic probability modelling approach is used here to evaluate the integrated risk associated with the preliminary e-flow requirements to provide for maintaining supporting service endpoints (fish, vegetation and invertebrates) or the ecosystem part of this assessment to meet the definition of the e-flow and later in the study where additional, particularly cultural and provisioning or social endpoints and other regulatory (additional ecosystem endpoints).

Step 6: Determining probable risk

In Step 6 (Figure 6) all the flow indicator components of the ecosystem used to establish preliminary e-flow requirements are integrated into the BN. The same rules or conditional probability tables (represented as stacked area graphs) are integrated into the model and combined to represent ecosystem components using additional conditional probability tables. The risk projections using the same ranking system (ideal to unsustainable) are used to represent the outputs of the models.

Step 7 & 8: Evaluation of integrated risk

In step 7 (Figure 6) the integrated risk to the ecological endpoints determined in Step 6 are evaluated. This allows for the consideration of the suitability of the indicator requirements used in Step 4 to determine the preliminary e-flows. If the integrated risk is suitable and aligns to the vision for the reach of river considered these e-flows are accepted as suitable integrated e-flow requirements for the site. If the evaluation of the preliminary risk results in a risk score that is too high, then in Step 8 an iterative process is followed to amend the flow requirements provided (step 4) into the hydrological statistical model to update the preliminary e-flows which can be re-evaluated in step 8. Here any potential discrepancies between preliminary e-flows where indicators are considered independently, compared to the holistic, integrated model results, need to be addressed. During this process new flow requirements can be generated and tested resulting in an acceptable, evidence-based risk profile that can meet the vision for the resource considered and from which suitable e-flows are determined. Take note, that while the uncertainty associated with isolated indicator requirements may be low-to moderate and uncertainty can increase through the use of the integrated probabilistic model, this can be mitigated/reduced through monitoring and testing and improved through iterative or adaptive modelling processes. This integrated approach meets good international, holistic e-flow determination considerations and conforms to the precautionary approach to water resources management.

2. Development of the online PROBFLO E-flow Framework Application Tool

The PROBFLO E-flow Framework Application (EFA) Tool is a web application incorporating Python and the Flask web application approaches into a comprehensive platform that combines data analyses following field based evidence collection with Bayesian Network (BN) probability modelling.

The features of the Application Tool are described below, while

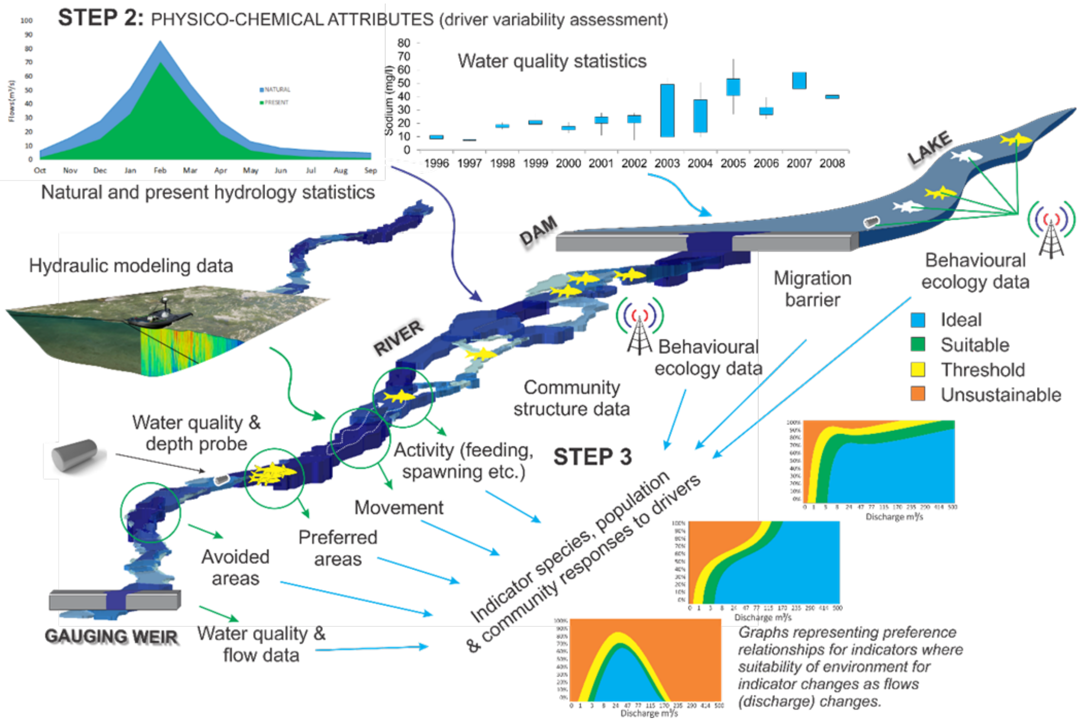


Figure 3. Step 3 of PROBFLO integrated e-flow determination approach. Indicator species, populations and community responses to drivers representing flow-ecosystem relationships for holistic e-flow determination. Note: flow-ecosystem stacked area graphs include ideal or pristine, sustainable or suitable, threshold of potential concern and unsustainable or unsuitable conditions in the graphs.

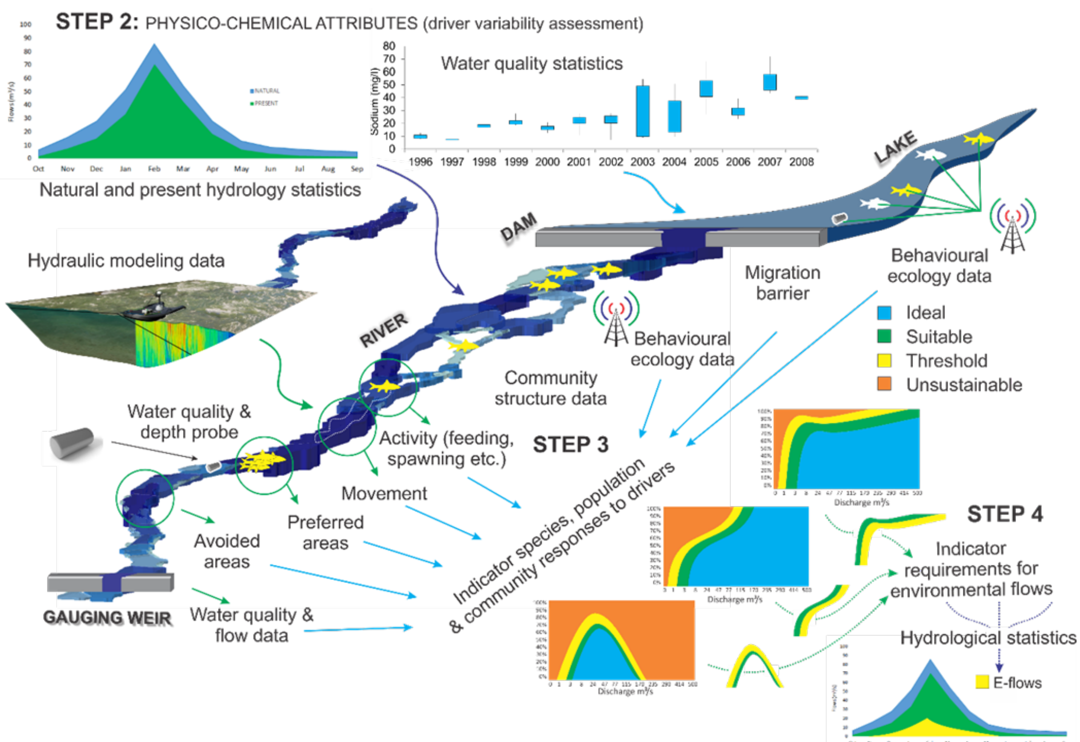


Figure 4: Step 4 of PROBFLO integrated e-flow determination approach. Flow-ecosystem relationships for indicators provided to the hydrologist as requirements for indicators to establish preliminary (indicator based) e-flow scenario.

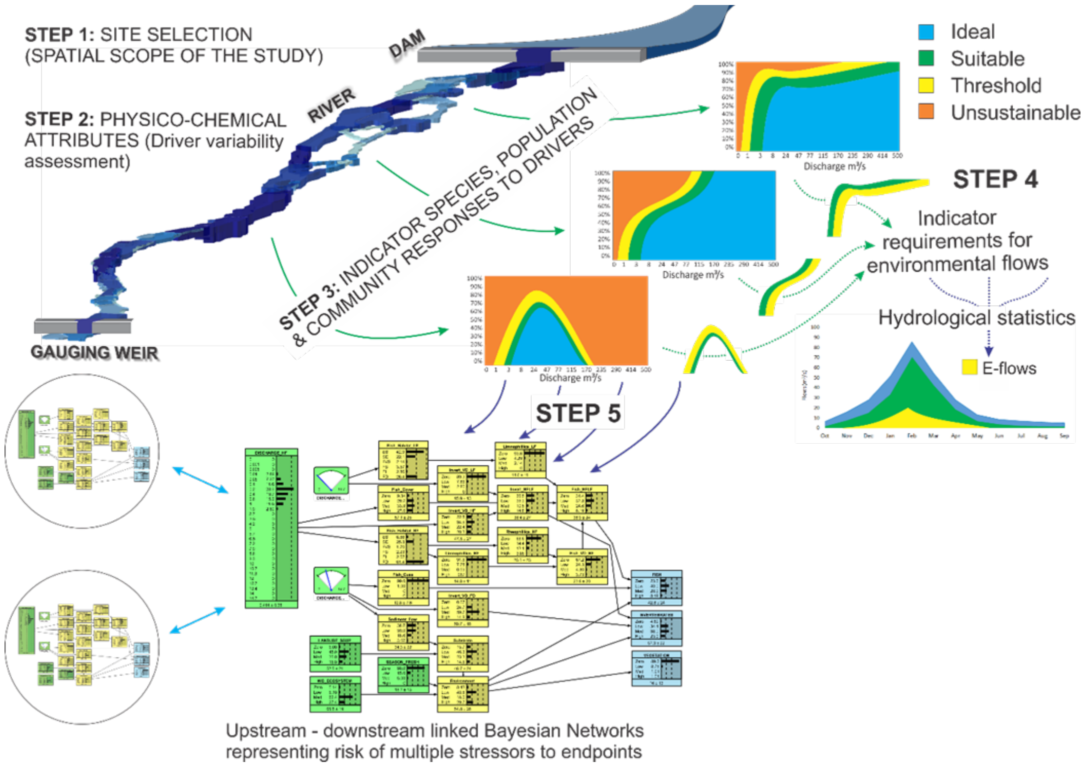


Figure 5: Step 5 of PROBFLO integrated e-flow determination approach. Use of flow-ecosystem relationships and non-flow ecosystem relationships to establish Bayesian Network probabilistic models for reach/multiple-reaches of ecosystems represented through connected models for holistic e-flow determination.

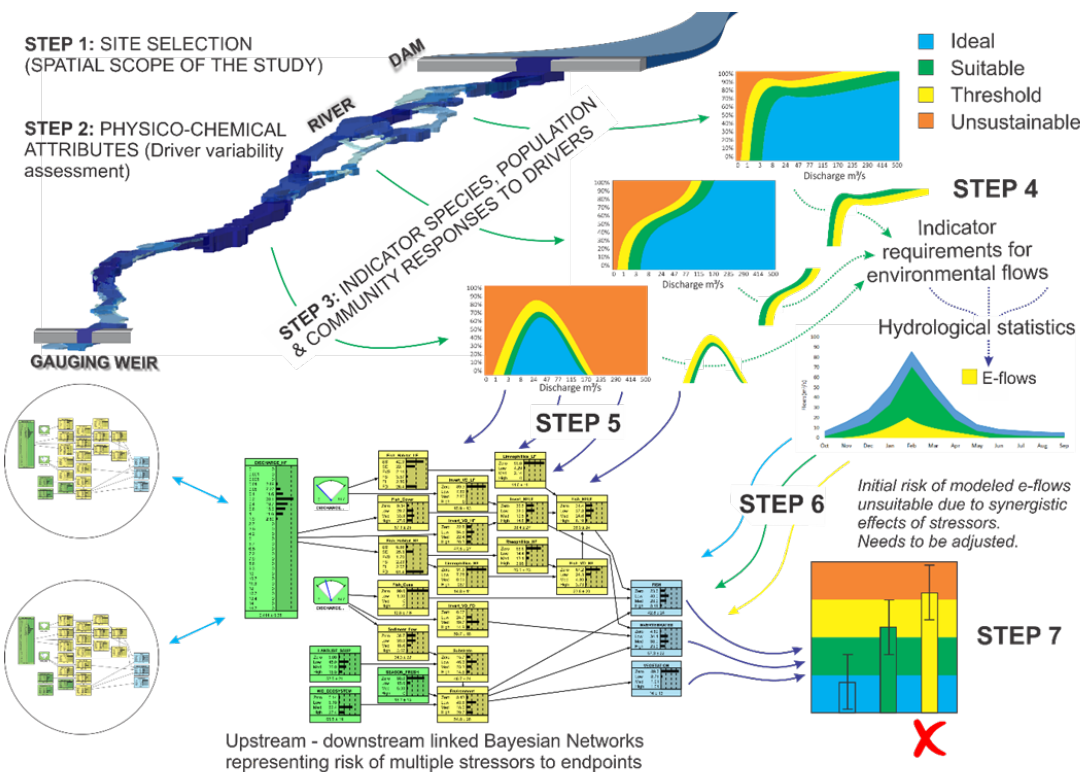


Figure 6: Step 6&7 of PROBFLO integrated e-flow determination approach. Bayesian Networks applied to determine probable risk of multiple flow and non-flow stressors to model endpoints that represent the ecosystem in an acceptable condition. Relative risk of natural, present day and preliminary (indicator based) e-flow scenarios evaluated.

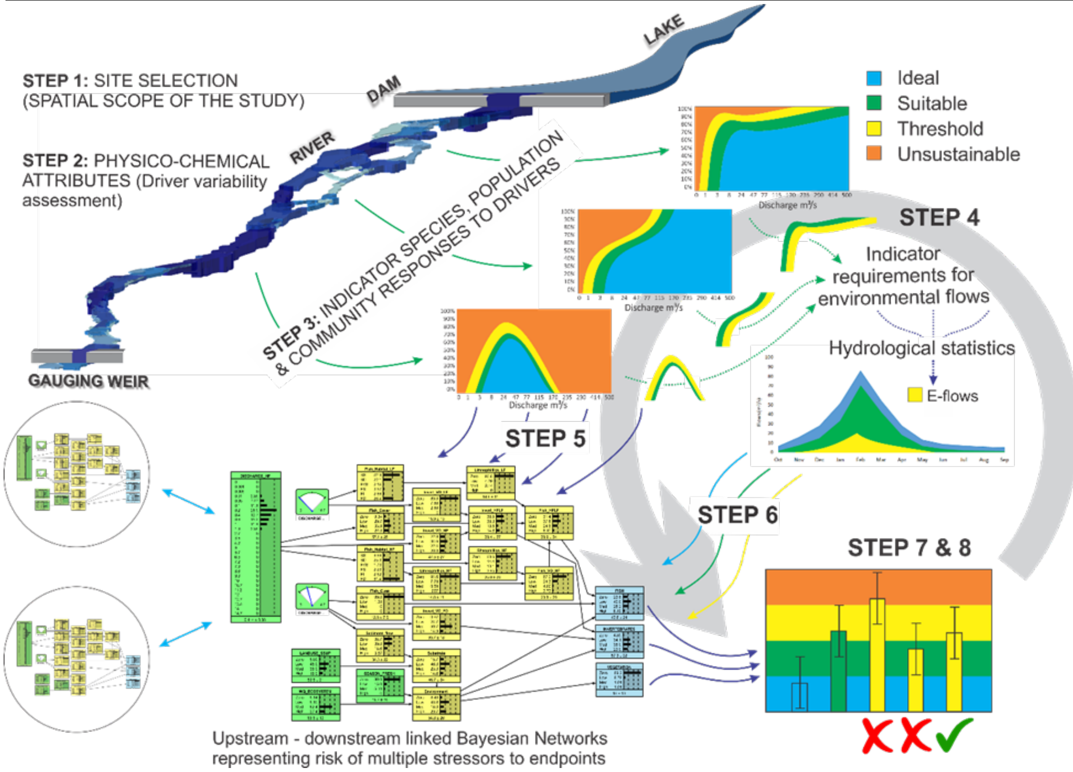


Figure 7. Step 8 of PROBFLO integrated e-flow determination approach. Bayesian Networks evaluation of risk of multiple stressors to preliminary (indicator based) e-flow requirements and revise to establish "integrated, holistic" e-flow requirements. This adaptive process can be applied through multiple iterations to result in a suitable "integrated, holistic" e-flow for each reach which is also integrated/synchronized between sites/reaches.

the documentation and specifications are provided in the Annexure.

2.1. PROBFLO EFA Tool

The PROBFLO EFA Tool (https://probflo.riversoflife.co.za) operationalizes e-flow frameworks established using PROBFLO, enabling stakeholders of the framework to generate and test any flow scenario, with associated non-flow variable conditions, and test their scenario using the established e-flow framework including probabilistic risk assessment. The use of the PROBFLO EFA tool provides the risk or socio-ecological consequences of any scenario for the range of social and ecological endpoints built into the framework, without the user having to develop BNs of their own and or interacting with the Netica probabilistic modelling tool. This approach allows stakeholders to test a scenario by modifying environmental driver options of existing PROBFLO Netica BN models. To achieve this the Netica model requires information from the user that can be uploaded into the input nodes using the PROBELO EFA tool front end. This includes flow information and non-flow related characteristics of the socio-ecological system as well as the hydrology for the scenario that is to be considered. This can be undertaken in three easy steps using the PROBFLO Application Tool.

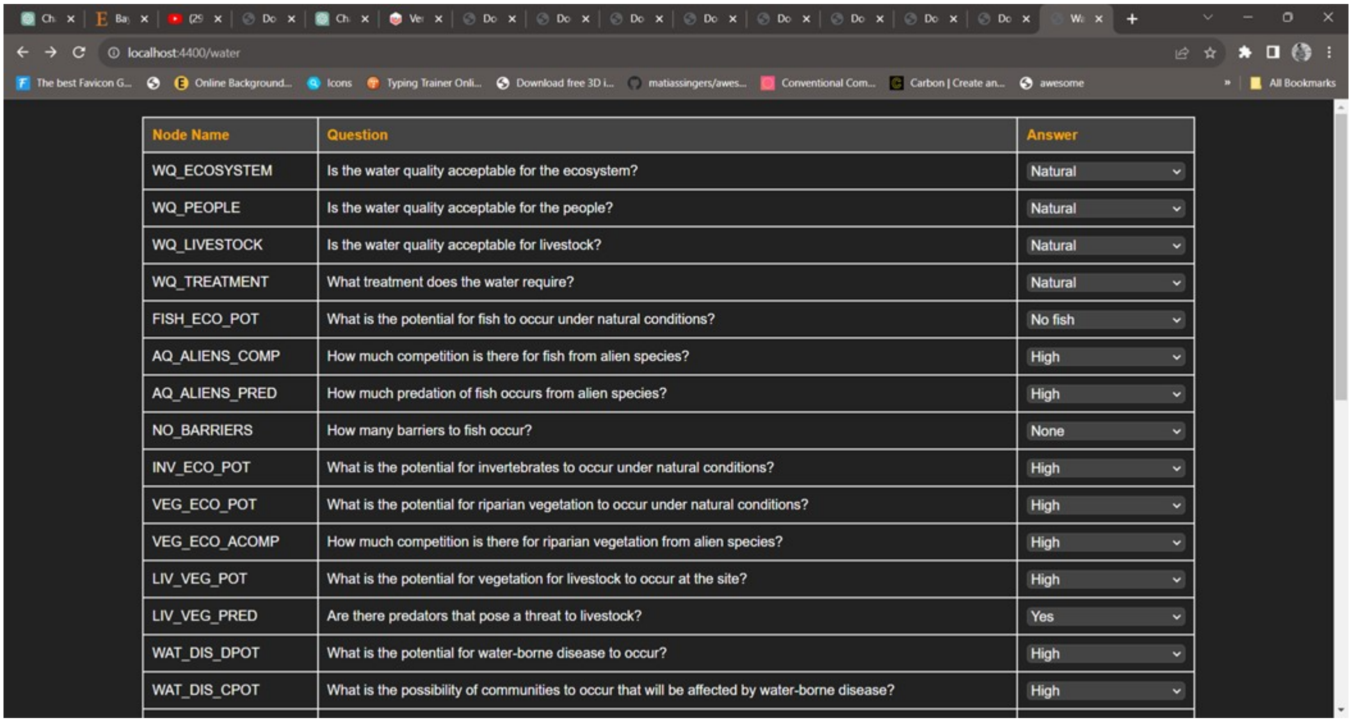
The PROBFLO e-flows framework has been developed using Microsoft Excel to capture, generate and process evidence and to generate flow(and non-flow)-ecosystem and flow(and non-flow)-ecosystem service relationships. This excel data is aligned to BN models generated in Netica that represent the socio-ecological systems being modelled for e-flow generation and the risk assessment. The PROBFLO EFA Tool incorporates these tools, and their data and allows users to change the state or condition of model variables/nodes which then automatically informs the risk models and generates risk outcomes in one easy process.

STEP 1. Frontend questionnaire

The PROBFLO EFA Tool easily allows the user to generate and test a flow scenario in a flow duration format that is uploaded to the PROBFLO EFA Tool as a Microsoft excel file. The user must also populate the state of and or condition of non-flow environmental variables for the holistic e-flows framework by completing the PROBFLO EFA Tool front-end questionnaire (example content in Table 1). In this user-friendly version of the application, the user selects a state/condition for each input variable from a drop-down (Figure 8). The options selected represent an input state distribution determined to be representative of the selection. The front-end selection, is transferred into an input distribution (see Annexure), which is automatically converted into a BN node distribution. Each drop-

Table 1: List of questions related to e-flows and ecosystem services that the user must answer in the PROBFLO Application Tool landscape for e-flow determination.

NETICA NODE NAME	ECOSYSTEM SERVICE QUESTIONS
WATER QUALITY (WQ) INPUTS	
State of WQ for ecosystem.	Is the water quality acceptable for the ecosystem?
State of WQ for human consumption.	Is the water quality acceptable for the people?
State of WQ for livestock.	Is the water quality acceptable for the livestock?
Treatment of WQ for human consumption.	What treatment of water quality occurs to mitigate effects of poor water quality for human consumption?
FISH INPUTS	
Potential for ecological importance and sensitivity of fish communities.	What is the potential for high diversity of fishes and species with conservation importance, relative to natural assemblages?
Threat of alien competing species.	How much competition is there for fish from alien species?
Threat of alien predatory species.	How much predation of fish occurs from alien species?
Presence of and size/impact of physical barriers.	How many barriers and what is the threat of barriers to fish movement/migration?
INVERTEBRATE INPUTS	
Potential for ecological importance and sensitivity of macroinvertebrate communities.	What is the potential for high diversity of macroinvertebrates and species with conservation importance, relative to natural assemblages?
Threat of alien competing species.	How much competition is there for alien species?
Threat of alien predatory species.	How much predation of fish occurs species?
Presence of and size/impact of physical barriers.	How many barriers and what is the threat of barriers to macroinvertebrate movement/migration?
VEG INPUTS	
Potential for ecological importance and sensitivity of riparian vegetation communities.	What is the potential for high diversity of riparian vegetation species and species with conservation importance, relative to natural assemblages?
Threat of alien competing species.	How much competition is there for riparian vegetation from alien species?
Potential for livestock of local human communities to occur/use river.	What is the potential for vegetation for livestock to occur at the site?
Threat of predatory species.	Are there predators that pose a threat to livestock?
WATER BORNE DISEASE (WBD) INPUTS	
Potential for the occurrence of WBD vectors.	What is the potential for water-borne disease to occur?
Potential for human communities vulnerable to WBD.	What is the possibility of human communities to occur that will be affected by water-borne disease?
Intervention/mitigation measures for WBD.	Does human intervention occur to stop water-borne disease?
Potential for predators of WBD.	Are there predators of water-disease vectors?
RESOURCE RESILIENCE	
Potential for resource resilience to occur.	What is the potential for resource resistance to occur?
How have flow durations changed.	Has the duration of flow events (base flows, freshets and floods) changed?
FLOOD ATTENUATION	
Potential for natural features to attenuate floods.	What is the potential for flood attenuation to occur?
Potential for artificial features to attenuate floods.	Are upstream mechanisms in place to control floods?
RIVER ASSIMULATION	
Potential for resource assimilation to occur.	What is the potential for the river to assimilate pollution?
SOCIAL INPUTS	
Potential for tourism to occur.	What is the tourism potential in the area?
Potential of tourists to access river.	Is access available for tourism?
Potential for recreational and spiritual activities.	What is the potential for recreational and spiritual activities to occur?
Potential for wildlife to threaten tourists.	Is wildlife a threat to recreational and spiritual activities?
OTHER	
Potential for disrupted sediment supply from poor land use activities.	Has land use attributed to sediment supply?
Demand for water by human communities.	What is the demand for domestic water?
Contribution of ground water to human needs.	Does groundwater flows contribute to domestic water supply?
State of seasonality of freshets/floods.	How has seasonality changed freshets?
State of seasonality of base river flows.	How has seasonality changed base flows?



Node Name	Question	Answer
WQ_ECOSYSTEM	Is the water quality acceptable for the ecosystem?	Natural
WQ_PEOPLE	Is the water quality acceptable for the people?	Natural
WQ_LIVESTOCK	Is the water quality acceptable for livestock?	Natural
WQ_TREATMENT	What treatment does the water require?	Natural
FISH_ECO_POT	What is the potential for fish to occur under natural conditions?	No fish
AQ_ALIENS_COMP	How much competition is there for fish from alien species?	High
AQ_ALIENS_PRED	How much predation of fish occurs from alien species?	High
NO_BARRIERS	How many barriers to fish occur?	None
INV_ECO_POT	What is the potential for invertebrates to occur under natural conditions?	High
VEG_ECO_POT	What is the potential for riparian vegetation to occur under natural conditions?	High
VEG_ECO_ACOMP	How much competition is there for riparian vegetation from alien species?	High
LIV_VEG_POT	What is the potential for vegetation for livestock to occur at the site?	High
LIV_VEG_PRED	Are there predators that pose a threat to livestock?	Yes
WAT_DIS_DPOT	What is the potential for water-borne disease to occur?	High
WAT_DIS_CPOT	What is the possibility of communities to occur that will be affected by water-borne disease?	High

Figure 8. Screenshot example of the list of questions that need to be completed by the user

down list only has four options for example, Natural, Small change, Moderate change or Unacceptable. These four options are comparable to the Netica Application ranking states namely: Zero, Low, Medium, and High (see Annexure).

STEP 2. Upload file

The foundation of the PROBFLO EFA Tool includes selected ecological and social indicators of altered volume, timing, duration and frequency of flows. Some of these flow variables components/nodes, such as seasonality of freshets/floods can be manually inputted into the model (Table 1). The majority of flow/ecosystem and flow/ecosystem service relationships established during the e-flow determination of the PROBFLO Framework have been established by specialists and these nodes directly query the hydrology of a scenario included in the assessment in the form of a flow duration table (Table 2). The PROBFLO EFA tool requires a user to establish a flow duration table for a scenario in Microsoft Excel. This table must be uploaded to the PROBFLO EFA Tool as a part of the Front-end of the Tool (Figure 9). The PROBFLO Application Tool automatically queries the flow duration table to populate/ represent yearly discharge, flood discharge range, high and low flow discharge distributions. These flow attributes of a scenario have a range of flow-velocity and depth, flow-cover, flow-dilution, flow-ecological cue relationships that are built into the PROBFLO EFA Tool by specialists.

STEP 3. Load case file

The next step of the PROBFLO EFA Tool involves saving and uploading the scenario case file for the PROBFLO Framework scenario assessment. The PROBFLO EFA Tool automatically uploads the case file saved to the users computer. This occurs automatically by clicking on the Load Case File link (Figure 9).

2.2. PROBFLO EFA output

The PROBFLO EFA Tool outputs are generated automatically and include risk probability distributions for all of the endpoints considered in the PROBFLO Framework (Figure 13). Endpoints can only include those selected for the PROBFLO Framework. In this example case the endpoints available include:

- Supporting services:
  - Risk to fish community (FISH_ECO_END)
  - Risk to riparian vegetation community (VEG_ECO_END)
  - Risk to macroinvertebrate communities (INV_ECO_END)

Table 2. Flow duration table example

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
0.1	164.0	280.7	449.8	563.7	1166.5	683.0	388.6	115.6	56.0	42.5	33.1	39.1
1	144.1	254.3	302.1	492.8	1142.4	608.8	247.6	94.5	55.2	38.4	32.6	36.7
5	48.3	167.3	220.1	352.9	558.6	353.1	142.1	68.3	42.4	31.3	25.8	25.4
10	39.7	138.2	162.3	299.3	385.1	236.4	112.3	54.8	36.8	29.0	21.2	22.9
15	30.9	118.0	140.3	223.1	299.3	200.5	96.9	47.3	33.0	24.6	19.6	18.0
20	26.1	96.2	127.4	181.2	250.1	174.0	82.2	43.8	29.0	22.9	18.4	17.0
30	21.4	68.5	108.0	121.7	118.2	120.4	62.9	36.5	26.2	19.7	15.7	14.7
40	18.0	52.4	93.8	93.1	88.9	84.8	52.2	31.1	22.1	18.1	14.7	12.7
50	16.1	44.5	77.3	76.1	76.7	56.4	44.1	27.2	20.5	15.5	13.1	12.0
60	13.0	35.6	57.7	66.1	61.4	49.5	38.2	24.8	18.8	14.6	12.1	10.8
70	10.8	28.4	46.7	53.3	49.8	39.4	32.9	21.3	16.1	14.0	11.5	10.0
80	10.2	21.7	33.2	44.7	44.4	34.5	24.5	17.8	14.6	12.1	10.9	9.0
85	9.9	18.6	30.9	39.9	40.1	31.9	22.8	17.2	13.7	11.3	9.5	8.4
90	8.6	15.1	26.5	33.8	36.7	27.8	21.7	15.9	12.7	10.5	9.0	7.6
95	7.7	12.0	21.6	29.3	30.8	24.5	19.7	14.8	11.9	9.8	8.4	7.2
99	6.9	9.1	14.3	24.1	25.6	18.0	14.6	10.2	9.0	7.7	7.3	6.7
99.9	6.5	7.2	13.9	23.9	22.1	14.5	12.0	9.4	8.1	6.5	7.3	6.7

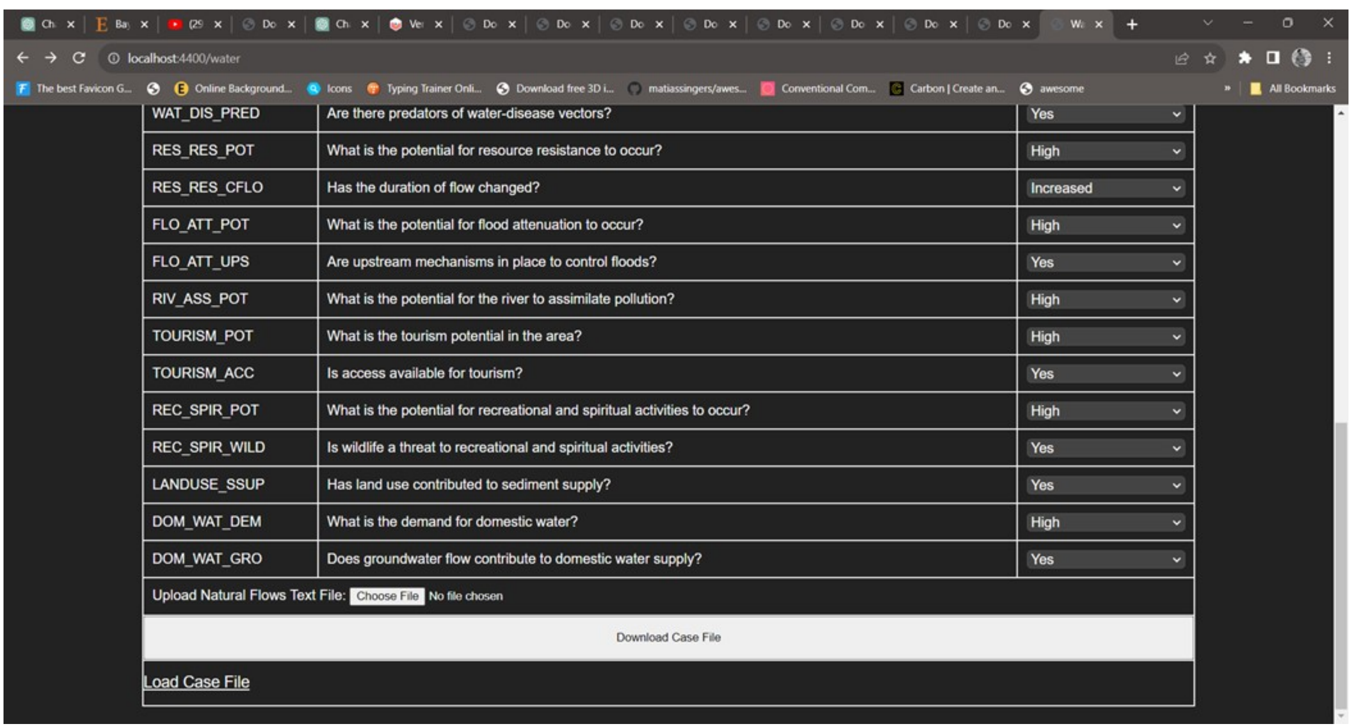


Figure 9. Example of the “Choose file” button and “Load Case File” link

- Provisioning Services:
  - Risk to the provision of vegetation for subsistence harvesting of local human communities (SUB_VEG_END)
  - Risk to the provision of fish for subsistence of local human communities (SUB_FISH_END)
  - Risk to the availability of grazing for the livestock of local human communities (LIV_VEG_END)
  - Risk to the availability of and condition of water for domestic use (DOM_WAT_END)
- Regulatory Services:
  - Risk to the potential for the river to attenuate floods (FLO_ATT_END)
  - Risk to the potential for the river to assimilate wastes (RIV_ASS_END)
  - Risk of water borne diseases occurring and impacting on human communities (WAT_DIS_END)
  - Risk to the potential for the river to be resilient to change (RES_RES_END)
- Cultural Services
  - Risk of the river providing suitable habitat and safety for human communities to carry out spiritual activities in the river (REC_SPIR_END).
  - Risk of the river providing wildlife and access to tourism activities (TOURISM_END).

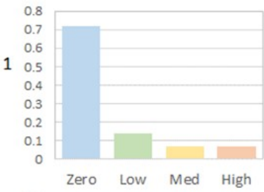
An example of the PROBFLO EFA Tool outcomes is in Figure 10. The PROBFLO EFA Tool provides risk distributions for all 13 ecosystem service endpoints including the probability (%) of risk for each of rank states (Zero, Low, Medium, High). These outcomes provide a range of information including for example (in order of importance): (1) the probability of high risk, (2) the most likely risk state for a scenario, (3) the probability of the endpoint of the river being in a moderate (med) or (threshold of potential concern) state, and (4) knowledge of the certainty/ uncertainty associated with the risk probability distribution.

In the example provided (Figure 13) representing the natural scenario for a reach of the lower Olifants River, the following information for this scenario is available:

- *Probability of high risk:* Under natural conditions, prior to the development of the water resources associated with the Olifants River the provision of water for domestic use to human communities, water disease potential and recreational/spiritual activities and tourism were all in a high-risk state. These high-risk dominated distributions include the potential for high risk to these end points to range between (51% and 35%). This is important and quickly identified provisioning, regulatory and cultural service attributes of the ecosystem that would be of concern. These results are attributed to the natural/pre-development state of the Olifants River (O'Brien et al., 2022). These variables are in a high risk as there is no infrastructure to provide water to human communities and in this area communities were very vulnerable to water borne disease and predation from Crocodiles. Crocodiles also threatened spiritual and recreational activities in this area. Figure 11 includes demonstration of use of PROBFLO EFA Tool to generate "Natural" and "Present" scenarios. To highlight the value of the outcomes of the study and demonstration of the PROBFLO EFA Tool you can see the considerable contrast between the potential for high risk to the supporting service endpoints in the "Present" state scenario.
- *Most likely risk state:* Here we have an opportunity to consider the shape of the risk distributions and can see that while the water for domestic use to human communities, water disease potential and recreational/spiritual activities and tourism will probably be in a high-risk state the fish, invertebrates and riparian vegetation communities (representing the supporting services) will probably be in a zero risk state. These results are consistent with the natural scenario. In Figure 12 (A-D) example risk distributions to demonstrate how you could obtain high likelihood distributions for "zero", "low", "moderate" and "high" risk could be possible. Note these "normal" distributions (including left or right skewed distributions) are expected but unusual distributions including bi-modal (Figure 12E) and uniform (Figure 12H) distributions are possible.
- Probability for threshold of potential concern state is then an important consideration. In a PROBFLO Framework the potential for moderate (med) risk is important as it is indicative of a socio-ecological endpoint of a scenario that could identify an ecosystems service attribute that may soon deteriorate into a high-risk state. In this case study there are no profiles with the moderate risk state dominating the distribution. In Figure 12C an example of a moderate dominated risk distribution is provided to demonstrate where risk is probably to result in a moderate state. These outcomes can be acceptable (for example e-flows targeting "altered" but acceptable/sustainable state) but should be allowed with caution as the potential for high risk is still high.

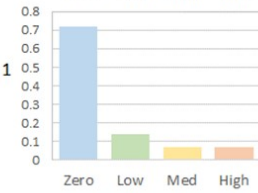
FISH_ECO_END

Category (state)	Value (%)
Zero	0.72
Low	0.14
Med	0.07
High	0.07



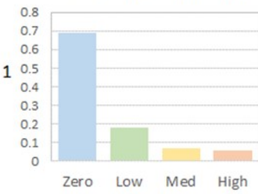
INV_ECO_END

Category (state)	Value (%)
Zero	0.77
Low	0.09
Med	0.07
High	0.07



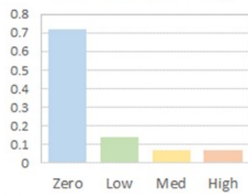
VEG_ECO_END

Category (state)	Value (%)
Zero	0.69
Low	0.18
Med	0.07
High	0.06



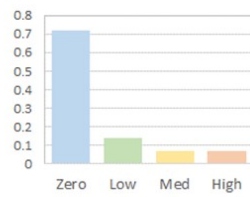
SUB_VEG_END

Category (state)	Value (%)
Zero	0.51
Low	0.3
Med	0.12
High	0.07



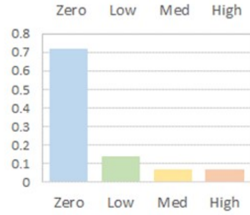
SUB_FISH_END

Category (state)	Value (%)
Zero	0.51
Low	0.3
Med	0.12
High	0.07



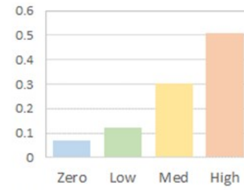
LIV_VEG_END

Category (state)	Value (%)
Zero	0.51
Low	0.3
Med	0.12
High	0.07



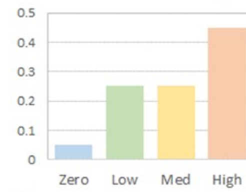
DOM_WAT_END

Category (state)	Value (%)
Zero	0.07
Low	0.12
Med	0.3
High	0.51



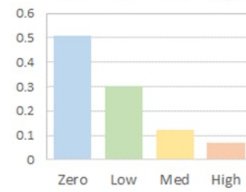
WAT_DIS_END

Category (state)	Value (%)
Zero	0.05
Low	0.25
Med	0.25
High	0.45



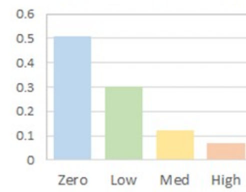
FLO_ATT_END

Category (state)	Value (%)
Zero	0.51
Low	0.3
Med	0.12
High	0.07



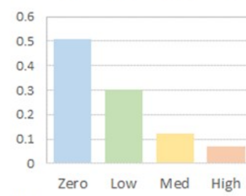
RIV_ASS_END

Category (state)	Value (%)
Zero	0.51
Low	0.3
Med	0.12
High	0.07



RES_RES_END

Category (state)	Value (%)
Zero	0.51
Low	0.3
Med	0.12
High	0.07



REC_SPIR_END

Category (state)	Value (%)
Zero	0.09
Low	0.25
Med	0.3
High	0.35

TOURISM_END

Category (state)	Value (%)
Zero	0.15
Low	0.15
Med	0.25
High	0.45

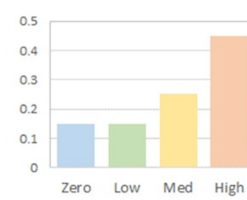
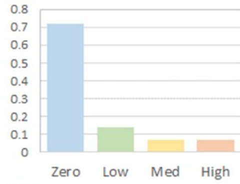


Figure 10. Example of the outcomes provided by the PROBLFO EFA Tool including the probability (%) of there being a high (pink), moderate (med, yellow), low (green) and zero (blue) risk to each endpoint included. This scenario is representative of a “natural” pre anthropogenic development scenario.

B. Natural scenario

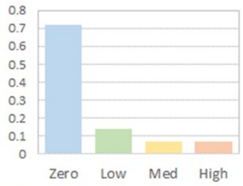
FISH_ECO_END

Category (state)	Value (%)
Zero	0.72
Low	0.14
Med	0.07
High	0.07



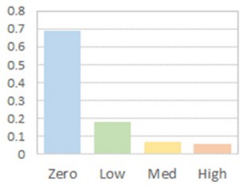
INV_ECO_END

Category (state)	Value (%)
Zero	0.77
Low	0.09
Med	0.07
High	0.07



VEG_ECO_END

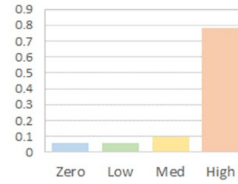
Category (state)	Value (%)
Zero	0.69
Low	0.18
Med	0.07
High	0.06



B. Present scenario

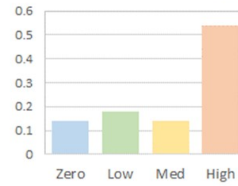
FISH_ECO_END

Category (state)	Value (%)
Zero	0.06
Low	0.06
Med	0.1
High	0.78



INV_ECO_END

Category (state)	Value (%)
Zero	0.14
Low	0.18
Med	0.14
High	0.54



VEG_ECO_END

Category (state)	Value (%)
Zero	0.08
Low	0.12
Med	0.18
High	0.62

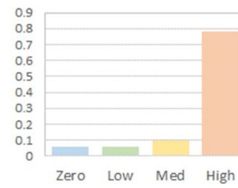
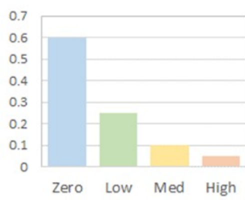


Figure 11. PROBFLO EFA Tool used to generate two comparable scenarios including the "Natural state" (A) scenario and the "Present state" (B) scenario for the supporting services alone.

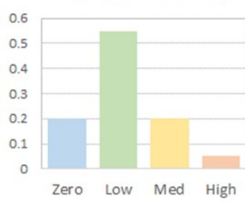
A.

Category (state)	Value (%)
Zero	0.6
Low	0.25
Med	0.1
High	0.05



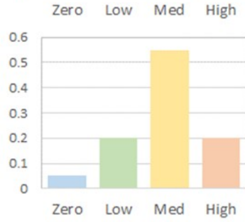
B.

Category (state)	Value (%)
Zero	0.2
Low	0.55
Med	0.2
High	0.05



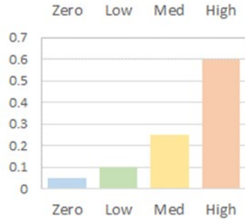
C.

Category (state)	Value (%)
Zero	0.05
Low	0.2
Med	0.55
High	0.2



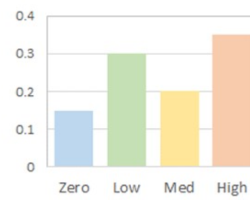
D.

Category (state)	Value (%)
Zero	0.05
Low	0.1
Med	0.25
High	0.6



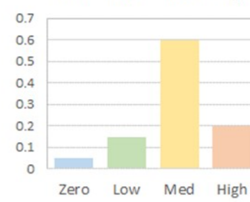
E.

Category (state)	Value (%)
Zero	0.15
Low	0.3
Med	0.2
High	0.35



F.

Category (state)	Value (%)
Zero	0.05
Low	0.15
Med	0.6
High	0.2



G.

Category (state)	Value (%)
Zero	0.2
Low	0.3
Med	0.3
High	0.2

H.

Category (state)	Value (%)
Zero	0.25
Low	0.25
Med	0.25
High	0.25

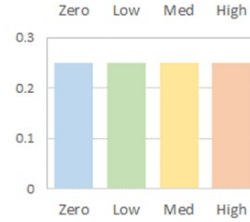


Figure 12. PROBFLO EFA Tool examples of risk profile to demonstrate potential likelihood of "zero"(A), "low" (B), "Moderate" (C) and "high" (D) occurring, and confidence uncertainty associated with varying risk distributions (E-H).

- *Certainty/uncertainty:* Apart from the formal model sensitivity/uncertainty assessment presented in the formal reports of the PROBFLO Framework report. Here certainty/ uncertainty in the outcomes are additionally available in the form of the shape of the distributions considered. In Figure 12 E-H examples of differences in confidence of results are provided including potential for a unimodal risk distribution shape with an unusually high potential (30%) for low risk and high risk (35%). With these types of outcomes more information is usually needed to improve our understanding of a potential high risk to the endpoint. Now compare the example distributions in Figure 12 F, G and H. Here certainty/uncertainty associated with the distributions are comparable. Consider first that while in Figure 12F results include a high relatively confident possibility of a moderate risk outcome, Figure 12H includes an equal uniform possible outcome of a zero, low, moderate and high risk state. This Figure 12H distribution suggests that there is either an equal chance of each state (unlikely) or there is insufficient data to result in a state dominated distribution. Compare also the distribution between Figure 12H, G and F. Figure 12G includes a low confident outcome with an elevated potential for a low and moderate risk (30% each) demonstrating some confidence in the distribution (compared to Figure 12H). On the occasion when limited data and or a poor understanding of the variables and flow-ecosystem or flow-ecosystem service relationships is included in an assessment, e-flow monitoring and implementation and increase certainty and the distribution could shift towards a more confident shape comparable to Figure 12B or C for example. This is the value of implementation using the PROBFLO EFA Tool.

3. Way Forward

Our team has developed the foundation PROBFLO EFA Tool application to allow stakeholders to access and use existing PROBFLO Frameworks. The team will continue to work on the development of this foundational tool. In particular we are working on the appearance of the tool, the incorporation of instructions and information to guide the use of the tool, and the manner used to present the outcomes of the models. We are also working on improvements to expand the tool's application to multiple sites and possibly multiple basins. We have identified some shortcomings and or issues with the application interface and with the communication between the PROBFLO EFA Tool application and the Netica API. We expect to be able to expand on the application and stakeholders will improved benefits and opportunities to use PROBFLO Frameworks.

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