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Risk Assessment of Water Quantity and Quality Stressors to Balance the Use and Protection of Vulnerable Water Resources

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EDITOR'S NOTE:

This article is part of the special series "Applications of Bayesian Networks for Environmental Risk Assessment and Management" and was generated from a session on the use of Bayesian networks (BNs) in environmental modeling and assessment in 1 of 3 recent conferences: SETAC North America 2018 (Sacramento, CA, USA), SETAC Europe 2019 (Helsinki, Finland), and European Geosciences Union 2019 (Vienna, Austria). The 3 sessions aimed at showing the state-of-the art and new directions in the use of BN models in environmental assessment, focusing on ecotoxicology and water quality modeling. This series aims at reflecting the broad applicability of BN methodology in environmental assessment across a range of ecosystem types and scales, and discusses the relevance for environmental management.

ABSTRACT

In developing regions of the world, valuable and vulnerable water resources are being used excessively. Through water resource development, multiple water quality, flow, and other stressors threaten the sustainable use and protection of these resources. Few attempts have been made to evaluate the synergistic effects of multiple water quality and flow stressors to socioecological attributes of systems that we care about in integrated water resource management. Regional scale ecological risk assessments evaluate the probable negative effects of multiple stressors, affecting dynamic ecosystems on multiple spatial scales. The present study demonstrates how multiple water quality, flow, and other stressors that cumulatively affect the sustainability of the lower Thukela River, South Africa, can be evaluated using the relative risk model, Bayesian network (RRM-BN) approach. This risk assessment facilitated the establishment of minimum water quality and flow requirements to maintain the sustainability of this system and make water resource use and protection trade-off decisions. In this case study, the risk of 10 water resources use and protection scenarios were evaluated in a regional scale ecological risk assessment of the socioecological attributes of the lower Thukela River. In addition we evaluated the consequences associated with these scenarios based on risk pathways of multiple sources, stressors, and receptors to endpoints that represent the sustainable vision of multiple stakeholders of the system. The outcomes of the present study have contributed to new evidence to improve the water resource use efficiency and protect important resources of the lower Thukela River, to ensure sustainability. *Integr Environ Assess Manag* 2021;17:110–130. © 2020 SETAC

Keywords: Multiple stressors Ecological risk assessment Water resources Sustainability Bayesian networks

INTRODUCTION

Water resources in developing regions of the world have high social and ecological value, and many vulnerable human communities depend on these resources for their livelihoods (King and Pienaar 2011; Fouchy et al. 2019). The development of these resources often results in the occurrence of multiple water quality, flow, and habitat-altering stressors that ultimately threaten the sustainable use and protection of these vulnerable resources (King and Pienaar 2011; Fouchy et al. 2019). Due to these multiple stressors, developing countries deal with water security, environmental degradation, and pollution issues (Alcamo et al. 2003; DEA 2012; DWA 2013). In particular, for water-scarce countries with highly seasonal and variable distributions of rainfall, water resources themselves are highly variable and usually unsustainable (DEA 2012). This water quantity problem is exacerbated by water resource development, including

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agriculture, urbanization, mining, and industries, resulting in additional stressors that negatively impact on the quality of the resources (Kathuria 2006; DEA 2012). Many developing countries experience conflicts between water resource use and protection, resulting in unsustainable resources (Dickens et al. 2019). In these developing regions, such as South Africa, suitable legislation is required to manage multiple stressors to achieve sustainability (Dickens et al. 2019).

Regional scale ecological risk assessments were developed to evaluate the probable negative effects of multiple natural and/or anthropogenic hazards, or multiple stressors, affecting dynamic ecosystems on multiple spatial scales (Landis and Wiegers 1997; Ayre and Landis 2012). Many tools are available to undertake regional scale ecological risk assessments, including the use of the relative risk model (RRM) incorporating Bayesian network (BN) probability modeling methods (Landis, Ayre et al. 2017; O'Brien et al. 2018). The RRM-BN approach is used to model socioecological systems and the cause-and-effect risk pathways of multiple sources to multiple stressors and then to multiple receptors within a range of habitats that ultimately drive ranked socioecological impacts or endpoints (Landis, Ayre et al. 2017; O'Brien et al. 2018). The relative risk scores are calculated for assessment endpoints and are compared across risk regions and between endpoints (Landis, Ayre et al. 2017). This approach has been used internationally at different spatial scales and on various source, stressor, and endpoint combinations (Ayre and Landis 2012; Hines and Landis 2014; Herring et al. 2015; Landis, Markiewicz et al. 2017). The approach has been used to evaluate the risk of multiple stressors to social and ecological endpoints, including provisioning and regulating ecosystem services and biodiversity and important ecosystem processes, respectively. The RRM-BN approach is a transparent and adaptable, evidence-based probabilistic modeling approach that can also incorporate expert solicitations and explicitly address uncertainty. The approach allows for the evaluation of both social and ecological consequences of altered flow and nonflow drivers of socioecological systems (O'Brien et al. 2018). In Africa this approach has been used to evaluate the effects of altered river flows, including the quantity and timing of water flows needed to meet the sustainable requirements of freshwater and estuarine ecosystems and nonflow variables (Poff et al. 2010; Arthington et al. 2018; O'Brien et al. 2018).

In South Africa, the National Water Act of South Africa (NWA 1998) has been established to protect, use, develop, control, conserve, and manage water resources in a sustainable and equitable manner for the benefit of all (DWAF 1999). Through this legislation and complementary regional policies (King and Pienaar 2011), regulators and stakeholders are attempting to achieve a balance between the use and protection of water resources. These processes consider limited knowledge of the socioecological systems being used and how attributes of these systems interact with each other and affect social and ecological endpoints of the system we care about. Ecological risk assessments can contribute to sustainable water resource management in these situations through the use of available evidence and solicitations from regional and international knowledge and case studies to characterize the possible risk of stressors on the receiving ecosystem (Landis, Markiewicz et al. 2017; O'Brien et al. 2018). This can contribute to improvements of the environmental performance of water resource use activities throughout South Africa including the socioecologically important lower reach of the Thukela River.

The Thukela River case study

The Thukela River in the KwaZulu-Natal province of South Africa is the second largest river in the country with a total catchment area of 29 042 km^2 (DWAF 2003a, 2004a). From the source of the river in the Drakensberg Mountains, the Thukela River meanders through central KwaZulu-Natal and discharges through the Thukela Estuary into the Indian Ocean, providing important resources not just to the communities within the catchment but also to the people of South Africa and its growing economy (DWAF 2003a; DWA 2013). Various transfer schemes, including the Thukela-Vaal transfer scheme, provide water to other areas within South Africa, and industrial areas like the Ladysmith and Newcastle complexes as well as the Sappi Tugela pulp and paper mill in Mandeni are reliant on the water resources supplied by the Thukela catchment (DWA 2013). The extensive utilization of the rivers within the Thukela catchment has resulted in various water quality, quantity, and habitat stressors that affect both the social and ecological aspects of the system (DWAF 2004b).

The Thukela River is ecologically important (DWAF 2003c, 2003d; DWS 2014) and provides ecosystem services for vulnerable local and regional African communities and is closely linked to the well-being of the offshore marine environment (De Lecea and Cooper 2016). The Thukela River enters the Indian Ocean at the broadest point of a continental shelf called the "Bight," which is part of the uThukela Marine Protected Area (De Lecea and Cooper 2016; DEA 2019). The water from the Thukela River accounts for more than 35% of the freshwater entering the Bight and forms a large organic matter plume that spreads into the sea and forms the offshore Thukela Banks (De Lecea and Cooper 2016). The riverine nutrient input from the Thukela River is vital for the ecology and biology of the Thukela Banks and the Bight, but reductions in freshwater outflow and sediment loads can have negative impacts on the estuarine system as well as on the marine ecosystems (De Lecea and Cooper 2016).

The state of the lower reach of the Thukela River and Estuary have both been established as largely modified, indicating that a large loss of biota, natural habitat, and basic ecosystem functions has taken place (Kleynhans and Louw 2007) from 2008 to 2016, and moderately modified, indicating that although a loss of natural habitat and biota has occurred, the basic ecosystem function has remained relatively unchanged (Kleynhans and Louw 2007) from 2017 to 2018, which can mostly be attributed to the synergistic effects of land use activities and the severe drought the region endured in 2015 (Blamey et al. 2018). These results suggest that although key ecosystem processes are functional, some attributes of the biodiversity of the ecosystem may be negatively impacted as a result of altered state of water quality and/or quantity or habitat driver states.

The lower reaches of the Thukela River and Estuary (Figure 1) include the urban community and associated infrastructure of Mandeni, the Sundumbili settlement, the Isithebe industrial area, the Sappi Tugela pulp and paper mill, and extensive agriculture activities (DWAF 2003b; Vezi et al. 2019). The Sundumbili wastewater treatment works (WWTW), a textile and a vegetable oil factory, Tugela Rail, Sappi Tugela, and irrigation for sugar farmers downstream all impact the eMandeni Stream or Thukela River through water abstraction, discharge or both (DWAF 2003b). Upstream of the confluence with the eMandeni Stream is the Lower Thukela Bulk Water Supply Scheme, which was completed in 2017 (Umgeni Water 2017). This scheme initially abstracts 55 mL of water per day from a weir that has been constructed in the Thukela River, with Phase 2 of the scheme doubling the abstraction to 110 mL/d (Umgeni Water 2017).

The Sappi Tugela mill was established in 1953 in Mandeni and has both extraction and discharge points in the lower reach of the Thukela River (DWAF 2003b; Macdonald 2004). Partially treated effluent from the Sappi Tugela mill is released into the Thukela River approximately 500 m below the confluence of the Thukela River with the eMandeni Stream, 7 km upstream of the Thukela Estuary. This pipeline is dilapidated, resulting in breakages and associated short-term releases of this partially treated effluent into the eMandeni Stream and then into the Thukela River. Known ecological impacts associated with the Sappi Tugela pulp and paper mill and other sources include a significant reduction in O levels in the receiving ecosystem along with rise in chemical oxygen demand (COD), ammonia, and conductivity (DWAF 2003b, 2004b; Stryftombolas 2008). Oxygen levels in the eMandeni Stream have been reported to be lower than those in the Thukela River (Stryftombolas 2008). The impacts of the sources of stressors in the Thukela River may persist into the Thukela Estuary (Vezi et al. 2019). As indicated, the region has also faced one of the worst droughts in modern history, with flows ceasing in the river entirely during 2015 and 2016. These reduced flows exacerbate the stress associated with the anthropogenic use of the system. These combined stressors may result in irreversible changes to the

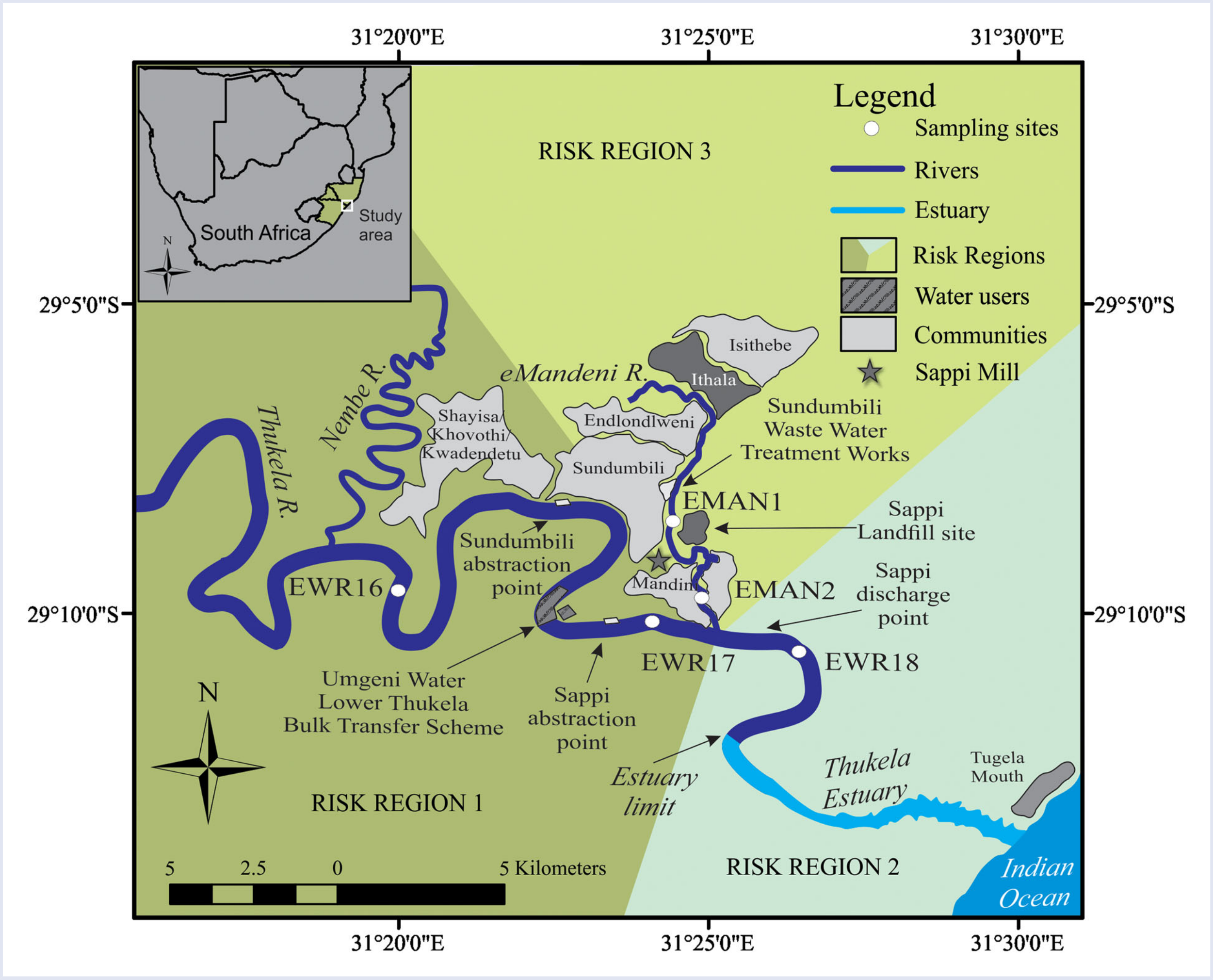

Figure 1. Map of the lower Thukela River, South Africa with sampling sites, formal sources of stressors, and other resource use development activities.

well-being of the socioecological systems due to lack of data describing these systems and their dynamic processes that make them difficult to manage.

The present study area includes the Thukela River from the confluence of the Nembe River to the Thukela Estuary, as well as the eMandeni Stream that flows into the Thukela River (Figure 1). The aim of the present study was to evaluate the socioecological consequences of multiple stressors to a range of social and ecological endpoints of the lower reach of the Thukela River. These endpoints represent the management objectives for the sustainable use and protection of the socioecological systems in the lower Thukela River region. This includes the evaluation of a range of water resource use options for the Sappi Tugela pulp and paper mill to consider the costs and benefits of alternative water resource opportunities before the existing deteriorating effluent pipeline is replaced. The present manuscript describes the implementation of the RRM-BN approach to evaluate the risk of water quantity and quality stressors in the lower Thukela River region to balance the use and protection of our vulnerable water resources.

METHODOLOGY

The 10 procedural steps of the RRM-BN regional ecological risk assessment were implemented in the present study according to the methods established in O'Brien et al. (2018), to evaluate and determine the risk of various scenarios (Table 1) related to the replacement or relocation of the deteriorating Sappi Tugela pulp and paper mill effluent pipeline. The RRM-BN is a holistic, regional scale ecological risk assessment based the environmental flows (e-flows) method that has been used throughout Africa to evaluate the socioecological consequences of multiple stressors, including flow and nonflow variables (O'Brien et al. 2018). Broadly, the procedural steps of the risk assessment include the establishment of a vision (Step 1) for the water resources being evaluated, which resulted in the selection of social endpoints associated with the maintenance of the livelihoods of local communities and of ecological endpoints that address biodiversity and ecosystem processes of the resources. Thereafter a literature review was undertaken for the present study area, and maps were established of water resources and associated ecosystem services (Step 2). The present study area was then divided spatially into 3 geographical risk regions to represent the dynamics of the ecosystems and allow endpoints to be evaluated in a relative and spatial manner (Step 3). Five sites were selected to evaluate risk associated with the activities of the Sappi Tugela pulp and paper mill (Figure 1). In Step 4, conceptual models that demonstrate the causal risk pathways from identified sources (including anthropogenic and natural activities or events) to stressors (e.g., water quality, flow, and habitat modifications), socioecological receptors in multiple habitats to endpoints, were developed. A ranking scheme was established for the present study to represent the condition of each variable of the study and risk to endpoints (Step 5). The risk was calculated (Step 6) using Microsoft Excel (Microsoft Corporation, https://office.microsoft.com/excel) and Netica (Norsys Software, http://www.norsys.com/) to construct the BN and determine the distribution of risk ranks that represent the risk profiles for each endpoint. These outcomes are then combined through multiplication of random assignments of risk ranks, based on endpoint probability distributions obtained from the BN for each of the 4 ranks used in the present study, into meaningful integrated social or ecological risk probability distributions for each risk region using Monte Carlo procedures undertaken with Oracle Crystal Ball software (Oracle Corporation, Oregon). These randomization evaluations are also used to quantify the effects of parameter uncertainty on the risk predictions (Landis 2004), with sensitivity evaluation procedures in Netica for uncertainty testing in this assessment (Step 7). A monitoring plan or program is required so that management can test the validity of the risk assessment (Step 8), which is then tested by implementation of management plan and the corresponding monitoring (Step 9). The last step of the approach is to communicate the outputs of the risk assessment and generate good practice recommendations for future sustainable management and risk mitigation (Step 10).

Vision and endpoints

The vision for the present study area representing the attributes of the socioecological system that is important to stakeholders was determined through the application of the resource quality objectives (RQO) approach for South Africa (Dickens et al. 2019). The RQO process includes 7 procedural steps to determine a suitable balance between the use and protection of water resources that are expressed as quality, quantity, habitat, and biota requirements for the resource. The outcomes of the formal RQO process are published in government gazette and become legal requirements that are binding on all stakeholders of water resources (DWA 2011). In the present case study, governmental stakeholders participated in the RQO determination process that resulted in preliminary RQOs; only when the formal RQO determination process for the whole basin is undertaken by the national Department of Water and Sanitation (DWS) will these RQOs be updated, synchronized with upstream RQOs, and then gazetted. The vision exercise involved a stakeholder engagement process in which representatives of the regulation, conservation, use, and resource management community, as well as civil society participated (Simunye Forum Meeting 2017). The RQO determination process included 1) defining the resource, 2) setting a vision to achieve a suitable balance between the use and protection of the water resources, and 3) determining the RQOs and numerical limits to represent the vision. As a part of this process, available regional water resource use and protection information was reviewed, summarized, and evaluated at the stakeholder workshops, in the context of regional legislation and policies. The Thukela River and Estuary were identified as important resources for management. The eMandeni Stream, however, has recently been augmented from a drainage line that has not formally been included in any national management plans into a

Table 1. The 10 water resource use scenarios selected for this risk assessment of multiple stressors to the socioecological endpoints selected for the Thukela River, South Africa risk assessment, including descriptions, hydrology, and ecotoxicology implications

Scenario	Title	Description	Hydrology	Ecotoxicology
SC1	Natural	Preanthropogenic scenario that represents 1900 conditions with limited water resource use.	Natural (natural hydrology based on available data prior to major dam development).	Preanthropogenic development conditions with no "unnatural" potential for water quality threats occurring.
SC2	Present	Scenario representing present observable conditions, including observed water resource use and protection scenarios (2015–2017).	Present (present hydrology, 1990 to current).	Observed (present) water quality alteration potential based on water quality monitoring of region from 2006 to date.
SC3	Present and environmental flows	Present scenario, including observed water resource use (SC2) and protection scenarios with assurance that environmental flows will be achieved (modeled scenario).	Current (current hydrology + environmental flows).	Observed (current) water quality alteration potential (SC2).
SC4	Alt Man Opt I: 100% eMandeni release at Sappi Tugela mill	Alternative water resource use Option I: Scenario based on 1) current water resource use scenario (SC2) and 2) observed ecosystem structure and function, with 3) an amended release scenario of existing effluent from the Sappi Tugela mill into the eMandeni Stream directly adjacent to the Sappi Tugela mill between sites EMAN1 and EMAN2.	Change in release location of current Sappi Tugela effluent flows into the eMandeni Stream between EMAN1 and EMAN2.	Change in release location of Sappi Tugela mill effluent with its water quality alteration potential into the eMandeni Stream between EMAN1 and EMAN2.
SC5	Alt Man Opt II: 100% eMandeni release at weir	Alternative water resource use Option II: Scenario based on 1) current water resource use scenario (SC2) and 2) observed ecosystem structure and function, with 3) an amended release scenario of existing effluent from the Sappi Tugela mill into the eMandeni Stream at the lower eMandeni Stream weir below site EMAN2.	Change in release location of current Sappi Tugela effluent flows into the eMandeni Stream below EMAN2.	Change in release location of Sappi Tugela mill effluent with its water quality alteration potential into the eMandeni Stream below EMAN2.
SC6	Alt Man Opt III: 50% reduction in flow of effluent and eMandeni release at Sappi.	Alternative water resource use Option III: Scenario based on 1) current water resource use scenario (SC2) and 2) observed ecosystem structure and function, with 3) an amended release scenario of 50% of effluent volume from the Sappi Tugela mill into the eMandeni Stream between sites EMAN1 and EMAN2.	Change in release location with 50% reduction of Sappi Tugela mill effluent flows into the eMandeni Stream between EMAN1 and EMAN2.	Change in release location of Sappi Tugela mill effluent into the eMandeni Stream between EMAN1 and EMAN2. With 50% reduction of Sappi effluent volume with existing water quality alteration potential.
SC7	Alt Man Opt IV: 100% eMandeni release at Sappi with 50% reduction in water quality alteration potential.	Alternative water resource use Option IV: Scenario based on 1) current water resource use scenario (SC2) and 2) observed ecosystem structure and function, with 3) an amended release scenario of existing volume (SC4) of effluent from the Sappi Tugela mill. With a 50% reduction in water quality alteration potential into the eMandeni Stream, released directly adjacent to the Sappi Tugela mill between sites EMAN1 and EMAN2.	Change in release location of current Sappi Tugela mill effluent flows into the eMandeni Stream below EMAN2.	Change in release location of Sappi Tugela mill effluent with a 50% reduction in water quality alteration potential of effluent into the eMandeni Stream between EMAN1 and EMAN2.

(*Continued*)

Table 1. *(Continued)*

Scenario	Title	Description	Hydrology	Ecotoxicology
SC8	Alt Man Opt V: 100% eMandeni release at Sappi Tugela mill with 75% reduction in water quality alteration potential.	Alternative water resource use Opt IV: Scenario based on 1) current water resource use scenario (SC2) and 2) observed ecosystem structure and function, with 3) an amended release scenario of existing volume (SC4) of effluent from the Sappi Tugela mill. With a 75% reduction in water quality alteration potential into the eMandeni Stream, released directly adjacent to the Sappi Tugela mill between sites EMAN1 and EMAN2.	Change in release location of current Sappi Tugela mill effluent flows into the eMandeni Stream below EMAN2.	Change in release location of Sappi Tugela mill effluent with a 50% reduction in water quality alteration potential of effluent into the eMandeni Stream between EMAN1 and EMAN2.
SC9	Alt Man Opt VI: 100% eMandeni release at Sappi with 50% reduction in water quality alteration potential of Sappi Tugela mill and other eMandeni effluents.	Alternative water resource use Option IV: Scenario based on 1) current water resource use scenarios (SC2) and 2) observed ecosystem structure and function, with 3) an amended release scenario of existing volume (SC4) of effluent from the Sappi Tugela mill. With a 50% reduction in water quality alteration potential of Sappi and other upstream effluents on the eMandeni stream into the eMandeni Stream, released directly adjacent to the Sappi Tugela mill between sites EMAN1 and EMAN2.	Change in release location of current Sappi Tugela mill effluent flows into the eMandeni Stream below EMAN2.	Change in release location of Sappi Tugela mill effluent with a 50% reduction in water quality alteration potential of Sappi Tugela mill and upstream effluents into the eMandeni Stream between EMAN1 and EMAN2.
SC10	Alt Man Opt VII: 100% eMandeni release at Sappi Tugela mill with 100% reduction in water quality alteration potential of Sappi Tugela mill and other eMandeni effluents.	Alternative water resource use Option IV: Scenario based on 1) current water resource use scenario (SC2) and 2) observed ecosystem structure and function, with 3) an amended release scenario of existing volume (SC4) of effluent from the Sappi Tugela mill. With a 100% reduction in water quality alteration potential of Sappi and other upstream effluents on the eMandeni stream into the eMandeni Stream, released directly adjacent to the Sappi Tugela mill between sites EMAN1 and EMAN2.	Change in release location of current Sappi Tugela mill effluent flows into the eMandeni Stream below EMAN2.	Change in release location of Sappi Tugela mill effluent with a 100% reduction in water quality alteration potential of Sappi Tugela mill and upstream effluents into the eMandeni Stream between EMAN1 and EMAN2.

Alt Man = alternative management; opt = option; SC = scenario.

Table 2. Social and ecological endpoints selected for the risk assessment to represent the vision or variables that stakeholders care about in the Lower Thukela River, South Africa

Endpoints	Description
Social endpoints	
Maintain supply of natural products (Nat_Products)	The supply and maintenance of the existing quality of fish, vegetation from the riparian zone for food and materials, and sand have been selected to represent the natural product supply for the study.
Maintain opportunities and environmental quality for recreation activities (Recreation)	The maintenance of the quality of the ecosystem to limit threats to human health and access and opportunities for recreation in the study area must be maintained.
Maintain water for abstractors (Water_Abstraction)	The socioeconomic value of the rivers in the study area, associated with the abstraction of water for urban and peri-urban communities, agriculture, and industry, must be maintained.
Maintain effluent assimilative capacity of the environment (Eff_Assimilation)	"Assimilative capacity" refers to the ability of the receiving ecosystem to remove water quality stressors, primarily through metabolic processes. The waterborne waste removal service of the rivers in the study area is of great value to the users and regulators of the rivers.
Ecological endpoints	
Maintain riparian vegetation well-being (Veg_Eco)	These ecological endpoints represent an important component of the ecological well-being of the aquatic ecosystems of the Thukela and eMandeni Stream.
Maintain fish community well-being (Fish_Eco)	
Maintain macroinvertebrate community well-being (Inv_Eco)	

perennial stream, through return flows from a local WWTW and industrial effluents. The vision of the eMandeni Stream has been aligned to the vision of the lower Thukela River that dominates the resource availability and use in the region. This includes:

- Maintain the 2017 (current) sustainable ecological well-being of the water resources, including condition of the physical, chemical, and biological attributes in the context of the biodiversity and key ecosystem process maintenance.
- Maintain the sustainable balance between the use and protection of water resources, which includes a safe and clean environment and promotes sustainable use for the benefit of all stakeholders. This includes maintaining existing abstraction volumes for basic human needs for local communities, agricultural and industrial use, provision of natural products, and recreational activities.

These visions were unpacked into preliminary RQOs for the present case study, in advance of the basin-scale implementation of the Resource Directed Measures procedures of the South African Department of Water and Sanitation (DWS), who will establish and legislate formal RQOs for the whole basin (Dickens et al. 2019). The RQOs established for the present case study describe the required attributes of the water quality, quantity, and habitat conditions and the well-being of a series of biological components for the resource at specified spatial locations within the study area. These RQOs were established at a stakeholder consultative process undertaken on 6 June 2017 through the local workshop (Simunye Forum Meeting 2017). These requirements were used to establish the endpoints in the present study that represent the current balance between the use and the protection of water resources that should be "maintained or improved." These objectives were selected as interim RQOs for the sustainable use and protection of the regional resources, prior to the formal basin-scale application of the RQO determination procedure as required by the National Water Act of South Africa (NWA 1998). The endpoints selected for this risk assessment include a range of social and ecological ecosystem indicator attributes (Table 2).

Sources and stressors

Various sources of stressors, including various local land use activities, and upstream contributions of stressors were identified that may impact on the endpoints listed in Table 2 and should be considered in Figures 1 and 2. Sources of stressors identified in the present study area contribute to various water quality and quantity, habitat altering, and disturbance to wildlife stressors (Figure 2). Water quality stressors are derived from anthropogenic activities, including elevated salts, organics, and altered system variables derived from the Sappi Tugela pulp and paper mill; toxicants derived from local industrial activities and urban and peri-urban centers; nutrient enrichment and organic contaminants from the local agricultural activities dominated by sugarcane farming; livestock farming and municipal WWTW and upstream sources. Hydrological stressors include alterations to the timing, volume, duration, and frequency of flows in the Thukela River in particular due to

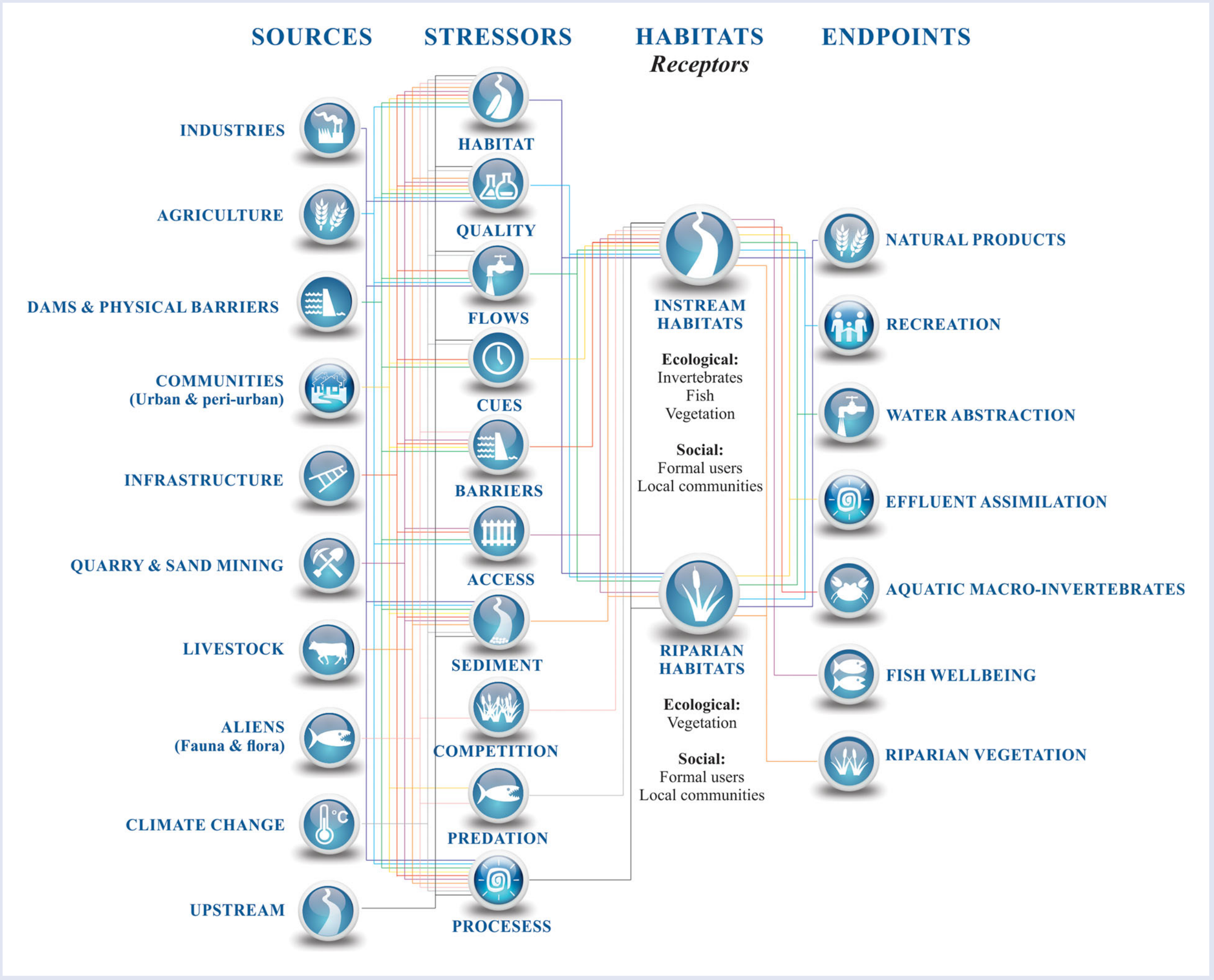

Figure 2. Conceptual model of the risk assessment, including causal risk pathways between sources, stressors, habitats, endpoints, and impacts for the lower Thukela River, South Africa.

upstream and regional diversions and dams. Habitat stressors are associated with local sand-mining operations and indirectly associated with reduced flows, resulting in changes to the sediment movement and deposition processes in the area and in disturbance to wildlife stressors associated with the excessive, illegal harvesting of fish for consumption, recreational activities disturbing wildlife, and alien fauna competing and predating on local species. These stressors were identified and evaluated and used as inputs in the risk assessment of multiple stressors affecting social and ecological endpoints established for the present case study.

Risk regions

Three risk regions (Figure 1) were delineated for the present study based on subquaternary catchment information and on the socioeconomic and ecological resource use scenarios. The resource use scenarios of the Sappi Tugela pulp and paper mill was a major determinant of the risk region delineation as alternative use scenarios for this activity were specifically considered in the present study. Multiple sources releasing effluent into the eMandeni Stream and the potential future diversion of effluent from Sappi Tugela into the stream supported the delineation of the stream and its catchment as a risk region (Risk Region 3, Figure 1). The cumulative contribution of upstream derived stressors in the Thukela River, above the confluence of eMandeni Stream (Risk Region 1), and the Thukela River downstream of the confluence (Risk Region 2) were selected as the other risk regions for the present study (Figure 1). Five sites within the risk regions were selected to evaluate the risk associated with the activities of the Sappi Tugela pulp and paper mill. These data were incorporated into the establishment of a BN for the risk assessment for each risk region, with additional refinement for relative risk assessment considerations for each site.

Conceptual model

The conceptual models developed in Step 4 are a critical step in the risk assessment process because they describe the cause–effect linkages for all the evaluated risk components, namely the sources, stressors, habitats, and impacts to endpoints selected for the present case study (Figure 2) (Wiegers et al. 1998; Ayre and Landis 2012; Landis, Ayre et al. 2017). Conceptual models were developed to consider all relevant sources, stressors, habitats, effects, and impact relationships with spatial and temporal considerations including macroinvertebrate, fish, riparian vegetation, and social endpoint models. The models represented in the format of the BN used in the assessment include exposure relationships with socioecological system structure and function variables that contribute to the exposure pathway of the model. The exposure component of the system is then combined with the effects component where they contribute to the overall risk to the endpoints of the assessment.

Ranking schemes

Ranking schemes allocated in Step 5 allow for the calculation of relative risks to each selected endpoint in the present case study (consider the Supplemental Data Table SI-4) (O'Brien and Wepener 2012). The 4 states that are commonly used in RRMs, namely zero, low, moderate, and high (Colnar and Landis 2007; O'Brien and Wepener 2012; Hines and Landis 2014; Landis, Ayre et al. 2017), have also been incorporated into the RRM-BN process. The states represent the range of well-being conditions, levels of impacts, and management ideals as defined in O'Brien et al. (2018) and are provided in Table 3.

In the present study to facilitate the risk assessment, the zero, low, moderate, and high ranks were assigned threshold relative risk scores of 25, 50, 75, and 100 for the BN and Monte Carlo randomization evaluations to integrate the social and ecological components. This ranking scheme represents the full range of potential risk to the ecosystem and ecosystem services with management options (O'Brien et al. 2018). By incorporating BN modeling into RRM-BN, the variability between ranks for each model variable can be represented as a percentage for each rank and is assigned a score 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 (Table 3) (O'Brien et al. 2018).

Data used to parameterize the models for the risk assessment, including rank thresholds established to represent the socioecological system being evaluated in the present study, are available in Supplemental Data Table SI-4. These data include all of the socioecological system variables or nodes (node names) selected for the models, network variable titles, ranks and associated modeling scores, rank definition and measures for variables, and justification for the use of the variables and evidence to describe their use in the risk assessment with references (example in Table 4).

Bayesian networks

The BN model was used in Step 6 to calculate the relative risk and incorporate management options by including indicators of the socioecological system of the present study area. Measures and interactions of variables are initially set up, justified, tested, and then applied (Supplemental Data). These models were analyzed individually or integrated using a range of BN modeling tools by using nodes representing variables that share the same indicators and measures. The graphic BN models make use of conditional probability distributions to graphically represent the relationships between the variables in the model (Figure 3). The model consists of parent or input nodes that provide the input parameters and child or conditional nodes that receive inputs from one or more parent nodes (Harris et al. 2017). The interactions between the parent nodes that result in the child node and the probability of all potential outputs based on different combinations of input variables are described in conditional probability tables within the BN (Herring et al. 2015). In the present case study we made use of the Netica BN software by Norsys Software (http://www.norsys.com/) to perform the assessments. The BN established for the present study has been provided as Supplemental Data.

The BNs were used in the present assessment to represent risks to current or present scenarios based on available data, field surveys, and expert opinion and then were used to model future use and protection scenarios. Scenarios were determined by stakeholders in relation to the aims and objectives of the present study and the need to evaluate alternative water resource use scenarios that specifically include quality and quantity variability of the receiving ecosystems. A socioecological model representing risk pathways from stressors such as users, alien species, and natural ecosystem drivers to ecosystem receptors representing the structure and function of the systems was developed. The model was calibrated using known historical socioecological ecosystem well-being characteristics compared with current or present-day conditions and then used to model future scenarios. For the present case study, 10 hydrological and/or ecotoxicological water resource

Table 3. Ranking scheme selected for the Thukela River, South Africa risk assessment, including ranks and descriptions

State and scores	Description
Zero (0–0.25)	Pristine state, no impact or risk, comparable to preanthropogenic source establishment, baseline or reference state.
Low (0.26–0.5)	Largely natural state and/or low impact or risk, ideal range for sustainable ecosystem use.
Medium (0.51–0.75)	Moderate use or modified state, moderate impact or risk representing threshold of potential concern or alert range, and possible failure threshold.
High (0.76–1)	Significantly altered or impaired state, unacceptably high impact or risk, and failure threshold.

Table 4. Extract from the justification table (Supplemental Data Table SI-4), including the socioecological system variables or nodes (node names) selected for the models, network variable titles, ranks and associated modeling scores, rank definition, and measures for variables and justification for the use of the variables and evidence to describe their use in the risk assessment, with references

Model variable title (BN node name)	Rank (score)	Rank definition and measure for variable	Justification	References
Cover suitability for fish (Fish_Cover_Depth)	Zero (25)	Ideal depth for indicator species to provide cover. Relates to preanthropogenic conditions.	Water column average depth plays an important role in providing habitat and cover for fish species. In this study *Labeobarbus natalensis* is a semirheophillic, relatively abundant, highly mobile, omnivorous indicator species, and *Oreochromis mossambicus* is a limnophillic species that was used in the study as an indicator of cover availability and suitability for fish.	Skelton 2001; Impson et al. 2008; Jacobs et al. 2016; data collected from this study.
	Low (50)	Suitable depth for indicator species available to provide cover.		
	Moderate (75)	Moderate loss of depth for indicator species, resulting in observable response of species to cover change.		
	High (100)	Significant loss of depth for indicator species, resulting in significant reduction of cover.		
Oxygen preferences of fish (Fish_SysVar_O2)	Zero (25)	Ideal DO levels with no significant influence to indicator species health and/or well-being.	DO is essential for maintaining fish health due to requirements for metabolic processes. Low levels of DO lead to negative consequences of individual fish health and hence, overall fish community well-being that consequently leads to mass die-off or fish kills. *Awous aeneofuscus* was identified as being significantly influenced by DO levels within the study area based on historical and present data. Accordingly, risk-associated levels were based on population abundance of this species.	
	Low (50)	Suitable DO levels with minimal impact to indicator species well-being.		
	Moderate (75)	Moderate (TPC) impact to DO levels with considerable impact to indicator species well-being.		
	High (100)	Exceptionally low levels of DO with critical impact to indicator species well-being.		
Substrate suitability for macroinvertebrates: Vegetation (Inv_Subs_Veg)	Zero (25)	Ideal marginal vegetation substrate for maintenance of macroinvertebrate well-being.	The maintenance of marginal vegetation is important for supporting a diversity of macroinvertebrate species within the study area. The discharge required for maintaining vegetation as a substrate for macroinvertebrate species was based on the discharge required to maintain the average vegetation latitudinal distribution.	Thirion 2016
	Low (50)	Suitable marginal vegetation available with minimal impacts to macroinvertebrate well-being.		
	Moderate (75)	Low availability of marginal vegetation substrate with moderate impacts (TPC) to macroinvertebrate community.		
	High (100)	Critically low marginal vegetation substrate available with critical impact to macroinvertebrate well-being.		

(*Continued*)

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Table 4. (*Continued*)

Model variable title (BN node name)	Rank (score)	Rank definition and measure for variable	Justification	References
Suitability of flood frequency: 1 in 2 y floods (Veg_Freq__1in2)	Zero (25)	The ideal number of specified flood events to contribute to maintenance of indicator riparian plants in upper flood benches.	A range in flood frequency (number of events per year) to maintain the upper limit of the macro-channel of the Thukela River, including indicator riparian plant communities on the upper flood benches of the river channel.	Determined on site according to specific indicators that have responded to present day flow regime.
	Low (50)	Suitable number of events to maintain the riparian community on upper flood benches.		
	Moderate (75)	Number of events that represents the threshold of potential concern for the maintenance of riparian community on upper flood benches.		
	High (100)	Insufficient number of flood events or absence of floods, resulting in functional failure of vegetation community.		
Threat of nutrient loading to aquatic macroinvertebrates (Inv_Nutrients)	Zero (25)	Ideal nutrient concentrations to maintain ideal macroinvertebrate community and indicator species.	Measure of the nutrient (total N and orthophosphate) tolerance limits of selected macroinvertebrate taxa and communities expected to occur in the rivers of the study area.	Lite and Stromberg 2007; updated in this study.
	Low (50)	Suitable nutrient concentrations to indicator macroinvertebrate species.		
	Moderate (75)	Nutrient concentrations representing threshold of potential concern or maximum tolerances of total N and orthophosphate concentrations for indicator macroinvertebrates.		
	High (100)	Unsuitable nutrient concentrations, resulting in loss of macroinvertebrate biodiversity and significant shifts in community structures.		

BN = Bayesian network; DO = dissolved oxygen; TPC = threshold of potential concern.

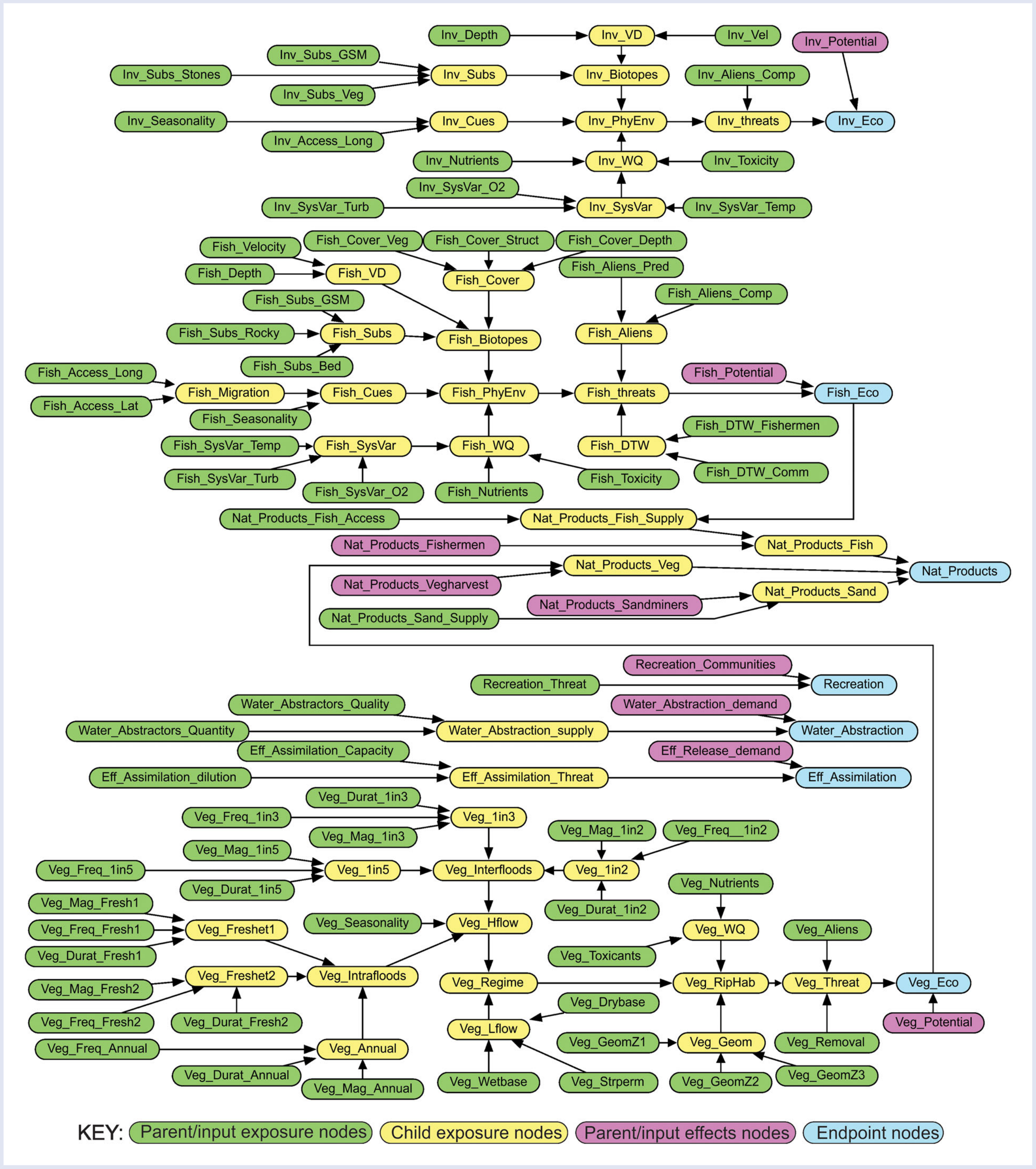

Figure 3. Bayesian network model for the Thukela River, South Africa risk assessment representing causal linkages between socioecological system variables selected to represent the system and the endpoints in the study. Model includes input exposure variables (green nodes), daughter exposure variables (yellow nodes), the effects (pink) variable, and endpoints nodes or variables (blue nodes).

use scenarios were selected for the evaluation (Table 1). These scenarios will allow for the consideration of the socioecological consequences of alternative water resource use options.

Uncertainty

The RRM-BN approach includes an evaluation of uncertainty (Step 7) so as to identify key drivers in the model and sources of uncertainty that may be impacting the overall uncertainty of the model (Ayre and Landis 2012). The results of the uncertainty evaluation provide context to the stakeholders and contribute to the water resource management decision-making process. The successful establishment and testing of risk hypotheses allows for the RRM to be validated, which reduced overall uncertainty. This includes application of the “Sensitivity to Findings” tool of Netica to evaluate the contribution of individual variables (nodes) to the risk outcomes and to use the Monte Carlo randomization approach in Oracle Crystal Ball software to integrate and test random effect of risk predictions (O'Brien et al. 2018).

In addition, various contributory methods, including the use of geographical information systems to facilitate with the mapping and exposure and effect pathway establishments, as well as the use of Monte Carlo and Bayesian techniques to address uncertainty, have been developed to complement, validate, and strengthen this approach (Landis and Wiegers 1997).

RESULTS

The sources, stressors, and habitats identified for each endpoint in Table 2 provided the data requirements to construct conceptual models (Figure 2) as BNs (Figure 3), with the green nodes showing the socioecological system structure and function variables, yellow nodes as the exposure pathways, pink nodes as the effect components, and blue nodes as the overall risk to the endpoints of the assessment. The Netica files for all the BN models have been provided as Supplemental Data.

To calculate the risk (Step 6) to the scenarios listed in Table 1, the outputs of an initial set up and calibration analyses were undertaken considering scenarios SC1 to SC4 only, where changes in hydrology were required (Supplemental Data Table SI-1, Figures SI-1 and SI-2). Due to the importance of evaluating the worst-case risk scenarios associated with temporal seasonal variability of the ecosystem during low flow or dry period flows, and the potential for the system to recover during the high flow or wet period flows, separate BN models were incorporated into the present study. Thereafter the additional relative socioecological risk to the endpoints associated with alternative management options for water resource use by the Sappi Tugela mill were evaluated, which pertained primarily to water quality modeling. Risk to the ecological endpoints was generally comparable, with a slightly higher risk observed to macroinvertebrates in the eMandeni Stream in particular at site EMAN2. This could be attributed to the limited diversity and general tolerance of fish that naturally occurred in the stream. Interestingly, the only time that the fish were at a greater risk (53.5%, ±23.1) in the eMandeni Stream compared to the macroinvertebrates (51.8%, ±24) and vegetation (44%, ±22.7) was during the high flow for SC3 at site EMAN1 (Supplemental Data Table SI-1, Figure SI-1). It should be taken into consideration, though, that the risk to EMAN1 during SC3 represents the e-flow requirement where flow from the river would be provided to meet the requirement of the fish at this site, but water quality issues associated with upstream WWTW would still pose a risk to the well-being of the fish endpoint.

Temporal trends include an increase in risk to all endpoints at all sites associated with the scenarios SC1 to SC4 during low flow conditions compared to high flow conditions (Supplemental Data Table SI-1, Figures SI-1 and SI-2). This is attributed to the natural seasonality of the rivers, including a reduction in flows during low flow conditions. Interestingly, in the eMandeni Stream, when seasonality of the stream is affected through the augmentation of the stream due to WWTW releases, the temporal variability of risk is reduced. Results also include a noticeable increase in risk, from low to medium, to the ecological endpoints from SC1 “Natural” to SC2 “Present” as expected. Although recent biophysical monitoring of the stream demonstrates an improvement from the mid-2000s, the well-being of the eMandeni Stream ecosystem is noticeably poorer compared with modeled natural conditions. Comparisons between sites include a considerably greater risk to the ecological endpoints in the eMandeni Stream (medium to high risk) relative to the Thukela River (low to medium risk). The latter can be considered to have a relatively greater resilience compared with the former. The risk to the ecological endpoints during SC4 in the eMandeni Stream will increase considerably if the effluent scenario is altered and effluent is released into the stream. Although the Thukela River is relatively more tolerant or resilient to change compared with the smaller eMandeni Stream, if the effluent produced by the Sappi Tugela Mill is diverted to the eMandeni Stream, a reduction in risk to the endpoints has been modeled to occur.

The average risk associated with SC4 (diversion of Sappi Tugela mill effluent to the eMandeni Stream) is largely attributed to a reduction in habitat diversity and sensitivity of the macroinvertebrate community, which will indirectly be affected by the high COD in the effluent. This 4-km reach between the alternative release point and the confluence with the Thukela River is hypothesized to be exposed to high risk of failure of the social and ecological endpoint, which will result in the biodiversity maintenance and ecosystem process part of the vision not being achieved. If this reach is considered a stabilizing zone, the benefit to the well-being of the Thukela River will be observable. From the model outputs, we hypothesize that the risk of the Thukela River exceeding the moderate and/or high risk threshold will be reduced to zero. This will be beneficial to the Thukela River. If additional water quality treatment is incorporated into the water resource scenarios, the calculated risk profile will change favorably, as reviewed in SC6 to SC10.

As expected, the risk posed to the well-being of the Thukela River ecosystem upstream of the confluence of the eMandeni Stream and the Sappi Tugela mill discharge point (sites EWR16 and EWR17; Figure 1) will not be affected by any alternative water resource use options. Findings of the assessment include an averaged “moderate” risk to the ecological endpoints in the Thukela River (Supplemental Data Table SI-1, Figure SI-1). This finding can be attributed to upstream water quantity and quality stressors and local threats. It should be considered that the water quality and hydrology statistics used to model the alternative water resource use options did not include the drought observed during 2015 and 2016. This uncertainty associated with the present condition can be attributed to the hydrological period used for the current and future scenarios, which ends prior to the drought. With these data, we hypothesize that

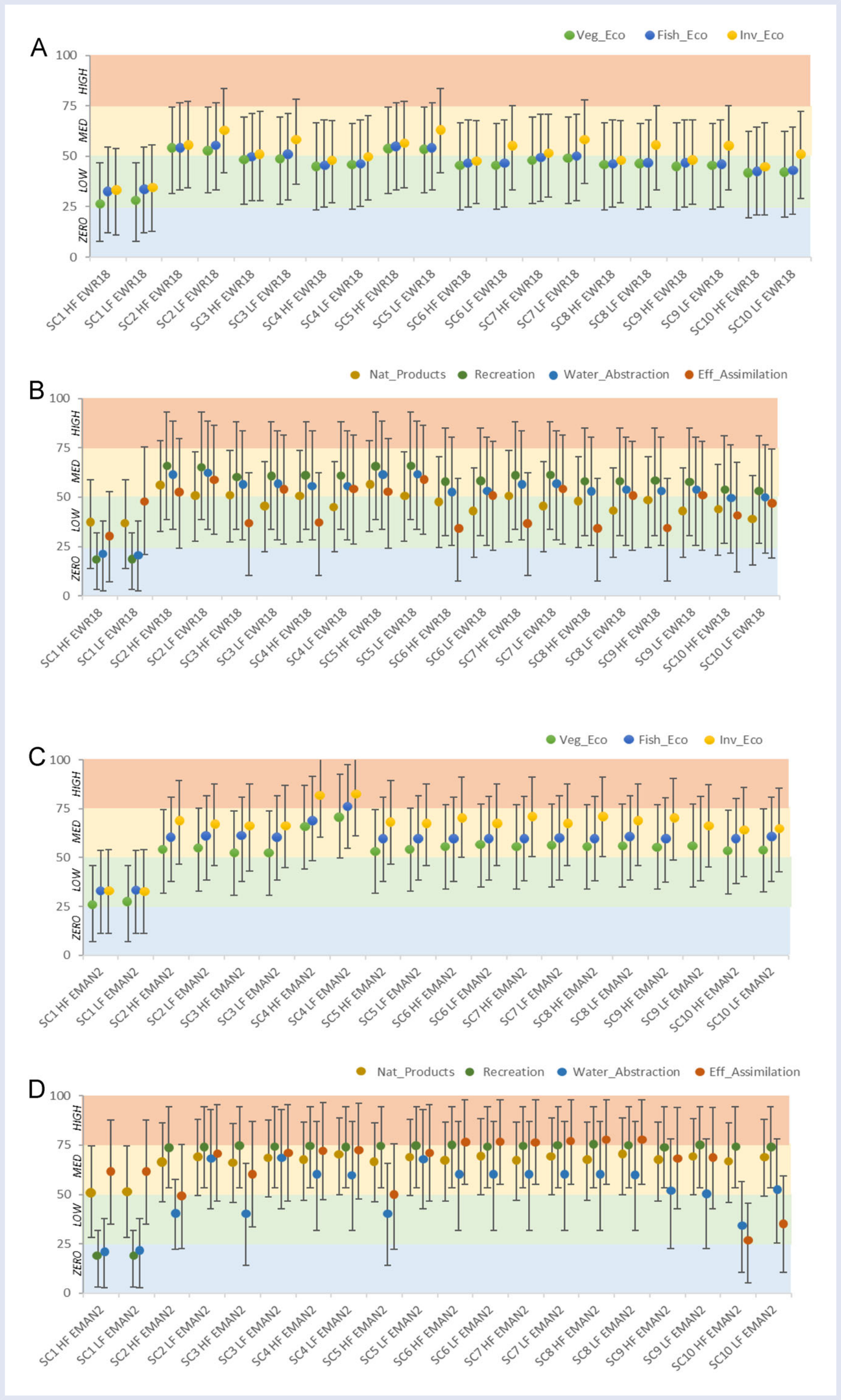

Figure 4. Average relative risk scores to the ecological (A) and social (B) endpoints for site EWR18 and the ecological (C) and social (D) endpoints for site EMAN2, during the high and low flow periods, with error bars representing standard deviation. Dots represent the median or likelihood, whereas lines represent range of possible risk. Eff_Assimilation = effluent assimilation; Fish_Eco = fish endpoint; HF = high flow; LF = low flow; Inv_Eco = macroinvertebrate endpoint; Nat_Products = natural products endpoint; SC = scenario; SC1 = natural; SC2 = present; SC3 = present and environmental flows; SC4 = 100% eMandeni release at Sappi Tugela mill; SC5 = 100% eMandeni release at weir; SC6 = 50% reduction in effluent release from Sappi Tugela mill; SC7 = 50% reduction in water quality alteration potential; SC8 = 75% reduction in water quality alteration potential; SC9 = 50% reduction in water quality alteration potential of Sappi Tugela mill and other eMandeni effluents; SC10 = 100% reduction in water quality alteration potential of Sappi Tugela mill and other eMandeni effluents; Veg_Eco = vegetation endpoint.

the system will recover if base flows associated with the e-flows are provided.

The results of the risk outputs to the social endpoints for SC1 to SC4 are highly variable (Supplemental Data Table SI-1, Figure SI-2). The results include a moderate to high risk in the eMandeni Stream under SC1 (natural) to the supply of natural products and the assimilative capacity of the stream to waste. These outcomes can be attributed to

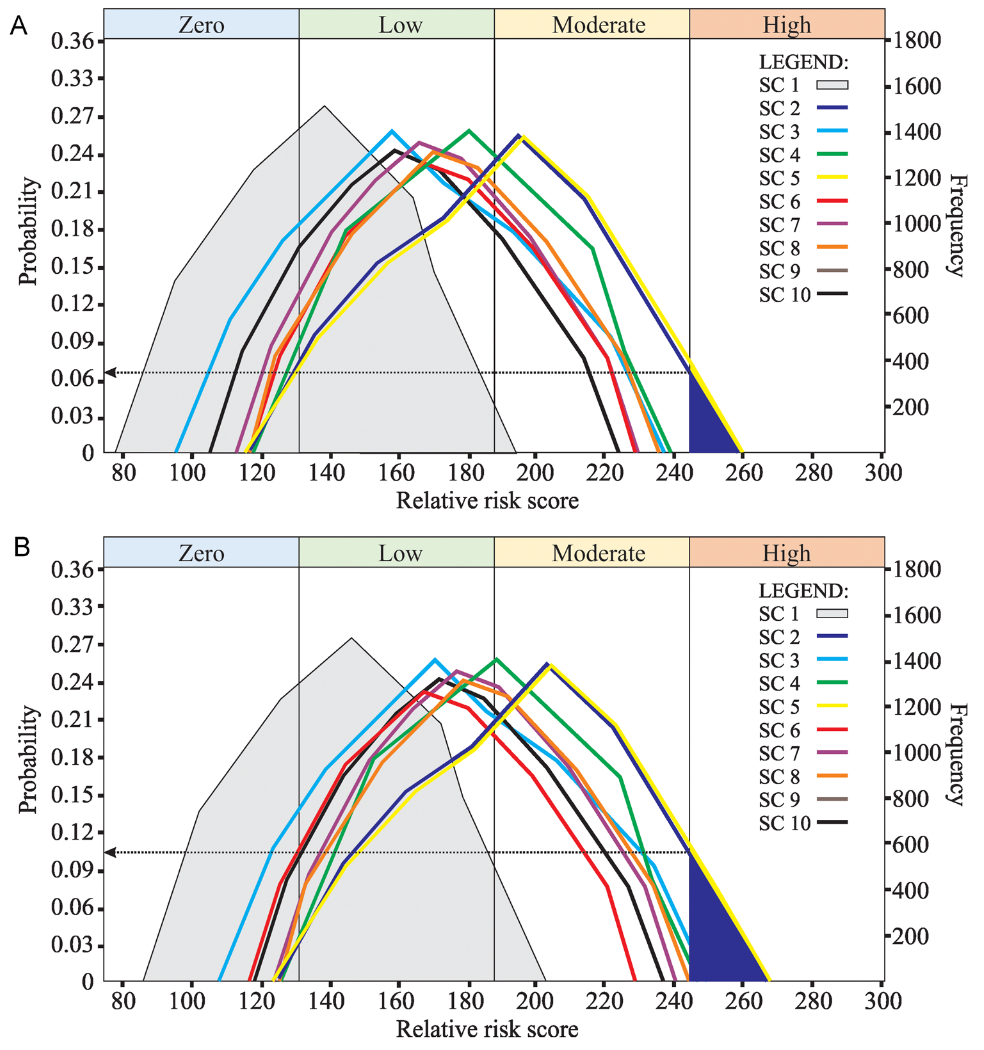

Figure 5. Integrated risk score distributions (simulated using Crystal Ball [Oracle Corporation, Oregon], 5000 trials) for site EWR18. Risk posed to ecological endpoints during high flow period (**A**) and low flow period (**B**). Risk rank categories included were zero (pale blue), low (pale green), moderate (pale yellow), and high (pale orange) threshold selected using Jenks natural breaks. Probable high risk emphasized through area shading. SC = scenario.

the relatively small size and associated provision of services of the eMandeni Stream. With the increase in use of the stream, the risk to many of the social endpoints has increased. On occasion, some endpoints benefit from resource use. These benefits include, for example, the relationship between the WWTW located on the eMandeni Stream, which has augmented the stream and reduced the risk to the water abstraction endpoint of the stream. In contrast, due to the effluent releases from the WWTW, the risk to the assimilative capacity of the system has increased. The risk to recreation and effluent assimilation endpoints was observed to be relatively larger in the eMandeni Stream compared to the Thukela River. Increases in water resource use options will result in additional risk to the endpoint. The eMandeni Stream has naturally been a very small tributary of the Thukela River. It has not been considered for delineation through the national Present Ecological State: Ecological Importance and Sensitivity (PES:EIS) study (DWS 2014). The change in risk to sites EWR17 and EWR18 in the Thukela River compared with site EWR16 on the Thukela River can be attributed to local water resource use activities that increase in the lower reach of the Thukela River study area.

In Figures 4A and 4B, the risk to the well-being of the ecological and social endpoints to the lower reach (EWR18) of the Thukela River during high and low flow for all the scenarios SC1-SC10 are included, respectively (Supplemental Data Table SI-3, Figure SI-3). Results include a relative increase in risk to the invertebrate endpoints during the low flow period, compared with the high flow or "recovery" period as expected. For the social endpoints, there was an increase in risk of up to 5.3% to the natural products endpoint but a decrease in risk of up to 17.4% to effluent assimilation during the high flow period. Scenario 5 risk results are comparable with SC2 (present state), for both the social and ecological endpoints, due to the location of the sites considered in the assessment as the release point is just

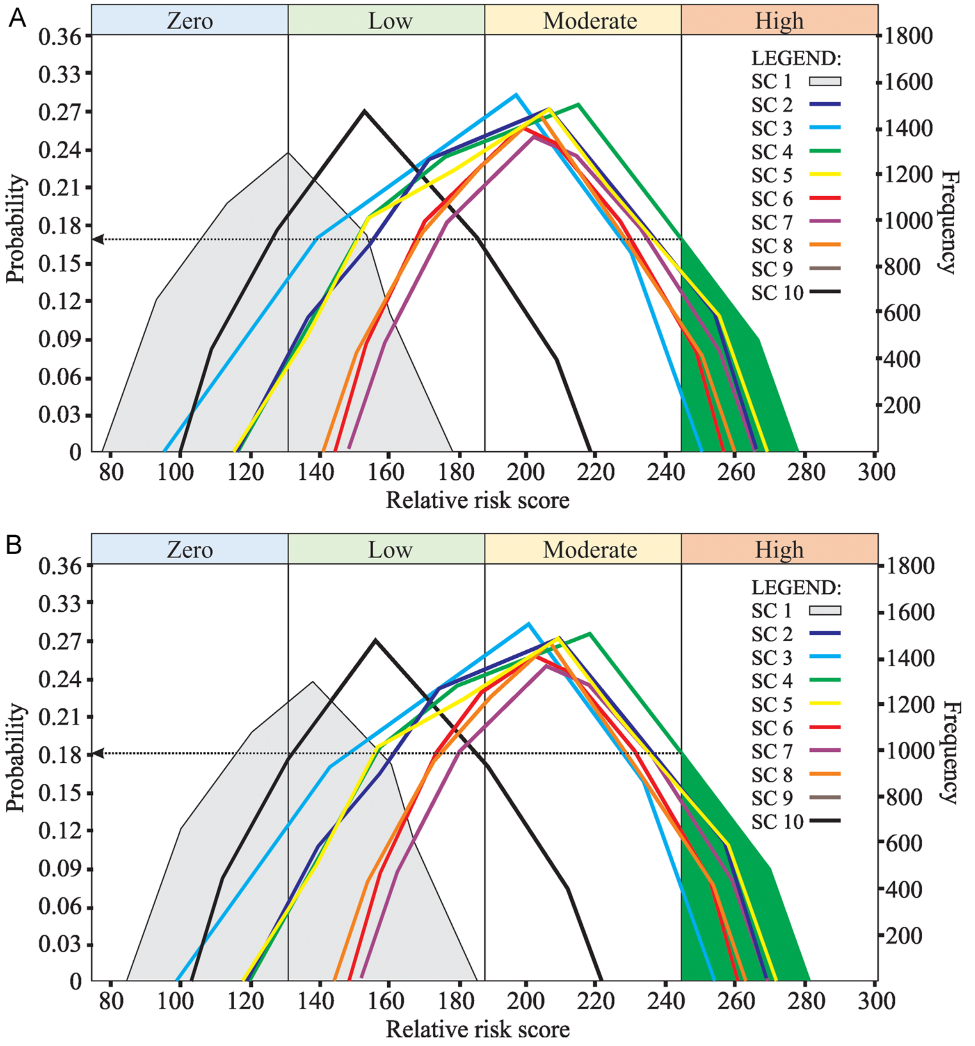

Figure 6. Integrated risk distribution projections (simulated using Crystal Ball [Oracle Corporation, Oregon], 5000 trials) to site EMAN2. Risk posed to ecological endpoints during high flow period (A) and low flow period (B). Risk rank categories included were zero (pale blue), low (pale green), moderate (pale yellow), and high (pale orange) threshold selected using Jenks natural breaks. Probable high risk emphasized through area shading. SC = scenario.

upstream of the confluence with the Thukela River and has been modeled as the same as the present scenario (SC2). Of importance is the reduction in risk to the well-being of the Thukela River at EWR18 observed for the ecological endpoints for SC4 during both high- and low-flow conditions. In addition, the reduction in risk to the well-being of the Thukela River at EWR18 during low flow conditions for SC6 to SC10 will benefit the system. These outputs demonstrate the positive benefit of releasing the Sappi Tugela mill effluent into the eMandeni Stream on the Thukela River compared to releasing the effluent into the Thukela River directly. Moreover, any additional treatment of the Sappi Tugela mill effluent and the combined effluent from the Sappi Tugela mill and the WWTW will contribute to the well-being of the system. The key determinant in these scenarios is the indirect effect of the CODs which significantly correlated with the poor state of the well-being of the Thukela River (Stryftombolas 2008), which is hypothesized to reduce through assimilation of the waste in the 4 km reach of the eMandeni Stream. In consideration of the costs and benefits of the alternative management options, the SC7 appears to have the best results. This includes treating 50% of the water quality alteration potential of the Sappi Tugela mill effluent that includes reduction in 50% of the COD from the mill. This will result in increases in oxygen to the Thukela River, which in turn results in risk reduction to the ecological endpoints.

In the eMandeni Stream, the effect of the Sappi Tugela mill alternative wastewater release strategy (SC4) will result in a significant increase in risk to the ecological (Figure 4C) and social endpoints (Figure 4D) of the ecosystem (Supplemental Data Table SI-2, Figure SI-4). Although the eMandeni Stream, which has been augmented into a stream, is relatively unimportant compared to the Thukela River in the context of the vision of the assessment and consideration of the natural state of the stream, it will be beneficial to the endpoints of the assessment if the effluent released from the Sappi Tugela mill is treated to reduce the risk to the well-being of the eMandeni Stream (SC9 and SC10). Although the outputs demonstrate that none of the scenarios will result in ideal water quality and flow requirements that represent the balance between the use and protection of the stream, due to the water quality and significantly increased flow into the stream, the well-being of the endpoint will improve considerably if all of the effluent from the Sappi Tugela mill and the WWTW is treated (SC10). Without complete treatment of the effluent, all the other mitigation scenarios are hypothesized to result in similar, comparable risk profiles to the ecological endpoints considered in the assessment. The well-being of the eMandeni Stream will return to an ecologically sustainable state only if the effluent from the Sappi Tugela mill and the WWTW is piped into a treatment works and then released into the Thukela River at a desirable quality that does not pose any negative threat to the biodiversity and associated ecosystem processes of the Thukela River. The uncertainty associated with wastewater releases from the Ithala Industrial complex into the eMandeni Stream will influence this output. During the late 2000s, the quality of the eMandeni Stream had reduced to critically modified conditions, indicating that the system had lost almost all of its biota, natural habitat, and ecosystem functions (Kleynhans and Louw 2007); this loss was partially attributed to the operations of the textile factories in the Ithala industrial complex. The closure of these factories has since resulted in an improvement in the quality of the river.

The application of the Monte Carlo permutation test with 5000 random iterations for the aggregation of all the ecological endpoints to the site EWR18 on the Thukela River reflects to the BN outputs (Figure 5). In this randomization assessment, the probability of approximately 10% exists to the failure of the ecological endpoints for SC2 (present day) and SC5, which is the alternative management Option II in which the Sappi Tugela mill effluent will be released into the eMandeni Stream at the weir on the lower section of the river (200 m upstream of the confluence). This risk projection can partially be attributed to the current condition of the instream habitat of the Thukela River with the synergistic effects of reduced flows and the existence of high CODs and temperatures that will affect the well-being of the river. The results demonstrate that the well-being of the Thukela River can probably be achieved by diverting the Sappi Tugela mill effluent into the eMandeni Stream alone, but the value of implementing SC6 and SC7 will potentially result in a more sustainable state to the well-being of the lower reach of the Thukela River. These outputs are based on current flows in the Thukela River from upstream of the present study area. Should upstream flows be reduced, the well-being of the lower reach of the Thukela River ecosystem will respond. The present assessment did not consider the relationship between flows in the Thukela River and the well-being of the nearshore marine biodiversity hotspot and associated Thukela Bight. The requirements of the Thukela Bight are potentially greater than the flows proposed in the present assessment and should be considered as a matter of urgency. If the subsequent e-flow of the lower reach of the Thukela River increases, it will be beneficial to the well-being of the Thukela River ecosystem.

In Figure 6, the results of the integration exercise include an increase from current 15% probability of failure to the well-being of the ecological endpoints that is excessive, to a 20% to 25% probability if SC4 is implemented without any mitigation measures. Only the SC2 (present), SC3 (present and environmental flows), and SC10 will result in a probable suitable balance between the use and protection of the ecosystem endpoints. These results suggest that the desired well-being of the eMandeni Stream cannot be attained unless the WWTW effluent is removed from the system or unless the WWTW and Sappi Tugela mill effluent is treated to achieve a 100% reduction in water quality alteration potential to the stream. Thereafter, SC6, SC7, and SC8 were considered, which all result in a likelihood of high risk of 12%, 15%, and 12%, respectively (Figure 5).

For the present case study, the “Sensitivity to Findings” tool of Netica was used to evaluate input variables. The important areas of uncertainty observed in the assessment include these:

- Cause-and-effect risk pathways are dependent on the understanding of the relationships between flow and nonflow driver variables and ecosystem processes and functions. Knowledge of these relationships is relatively limited, resulting in inherent uncertainty.
- The present case study addressed the socioecological consequence of alternative water use scenarios to the well-being of the ecosystem (based on endpoints) and associated availability and conditions of ecosystem services. The assessment did not address the social impacts associated with any visual and or aesthetic impacts of the developments.
- The well-being of the nearshore marine biodiversity hotspot off the mouth of the Thukela River and the Thukela Bight has repeatedly been linked to existing reductions in flows and associated sediment transport from the Thukela River. The water resources of the lower reaches of the Thukela River are currently being managed with consideration of the marine ecosystem and or requirements of the Thukela River for these associated marine ecosystems. It is speculated that future water resource developments are being considered without thought of the connectivity of the Thukela River to regional marine ecosystems. The direct effect of existing water resource development and possible future developments to the well-being of the marine ecosystems should be addressed.
- In the present case study, a simplified RQO method (DWA 2011) was implemented to establish endpoints for the assessment. These endpoints were established independently of catchment-scale water classification processes where use and protection scenarios for integrated units of analyses for the catchment will be

considered. For these endpoints to be accepted by regional stakeholders as suitable objectives to achieve the balance between the use and protection of the ecosystem, the formal water resource classification and RQO process for the Thukela River catchment should be undertaken.
- The effect of increased flows to the eMandeni Stream is poorly understood, and this affects the risk estimates.

DISCUSSION

Currently the Thukela River has been affected by reduced flows, alterations in sedimentation processes, and increases in waterborne wastes that include the effect of the Sappi Tugela mill effluent on the well-being of the lower reach of the Thukela River. The eMandeni Stream has also been altered through increased water volume and effluent being released into this small stream. The risk assessment included the consideration of the relative effect of releasing the Sappi Tugela mill effluent into the eMandeni Stream at Sappi, compared to the current situation in which the effluent is released directly into the Thukela River. Results from this scenario assessment include potential benefits to the Thukela River but a considerable increase in the risk to the eMandeni Stream. This increase will primarily affect the habitat quality, and a deterioration in water quality will influence the ecosystem well-being negatively.

In the present study, we have used the RRM-BN approach to demonstrate how multiple water quality and flow stressors have a potential synergistic effect on the well-being of the Thukela River socioecological system. We have considered multiple endpoints and scenarios and have demonstrated how the risk of multiple stressors currently affecting the Thukela River can be mitigated by redirecting the partially treated effluent from the Thukela pulp and paper mill into the eMandeni Stream and then improving treatment. The water resource management recommendations from this study will result in a better balance between the use and protection of the Thukela River while increasing the risk to the eMandeni Stream. This trade-off, and consideration of trade-offs between cost of treatment and benefit to the social and ecological system of the Thukela River, is now available. Now we have the evidence we need to consider alternative water resource use scenarios in the Thukela River and have made a submission to the regulating Department of Water and Sanitation to consider amending water use authorizations for the Sappi Tugela mill. Unfortunately regulators have dismissed the application, citing the National Water Act of 1998 prohibition of sacrificing 1 ecosystem for another. This response seems to be out of context of the present study and possibly related to the difficulty of dealing with trade-off decisions with competing environmental management objectives as described by Retief et al. (2013). In South Africa, stakeholders appear to be risk averse and resist real adaptive management due to the potential personal repercussions perceived to be associated with environmental mismanagement. In situations where decisions are difficult, people are predisposed to "do nothing" (Anderson 2003). Retief et al. (2013) argue that regulators should expect a high level of decision difficulty when dealing with trade-offs, especially when dealing with uncertainty and unfamiliar approaches.

Presently numerous holistic integrated water resource management (IWRM) methods (Horne et al. 2017) advocate the integration of multiple water quality and flow stressors in water resources management processes. Although these methods that are thought to be holistic consider the natural and unnatural (associated with anthropogenic stressors) variability of water quality, flow, and other stressors, and how ecosystems respond to these variabilities, the synergistic effect of multiple stressors is not considered. In developing countries where water resource use has become unsustainable and the majority of surface ecosystems are threatened, such as in South Africa (SANBI 2019), it is pertinent that technically correct holistic IWRM methods are established and implemented. These methods must have the ability to adequately represent the component of socioecological systems and how variables interact, and to model the causal effects of multiple stressors to multiple receptors to a range of social and ecological endpoints. Not only does this RRM-BN approach demonstrate that this is possible, but in addition it allows stakeholders to establish minimum water quality and flow requirements of ecosystems (i.e., e-flows) (e.g., O'Brien et al. 2018). The RRM-BN approach has successfully been used to evaluate the socioecological consequences of a range of water quantity and quality alteration development options offering stakeholders the opportunity to consider trade-off considerations between resource use and protection requirements. The approach has also been used to optimize the environmental performance of sources of multiple stressors in the present case study, including a favorable cost–benefit alternative to the water resource use status quo for the Sappi Tugela pulp and paper mill that is affecting the well-being of the socioecologically important Thukela River in South Africa.

CONCLUSION

The aim of the present study was to evaluate the socioecological consequences of multiple stressors to a range of social and ecological endpoints to the lower reach of the Thukela River and evaluate a range of water resource use options for the Sappi Tugela pulp and paper mill to consider the costs and benefits of alternative water resource opportunities before the existing deteriorating effluent pipeline is replaced. The RRM-BN approach demonstrated in the case study resulted in a range of risk projections from zero risk, ideal state dominated projections to all sites during the "natural" scenario, to acceptable low to moderate risk states for the Thukela River main stem for current conditions and moderate to high risk profiles for the eMandeni Stream. These results reflect the observed change in the well-being of the rivers in the present study area due to existing upstream stressors and local water quality, quantity, and habitat stressors.

To reduce uncertainty associated with the outputs of the risk assessment, it is recommend that existing monitoring programs be expanded to 1) validate the flow-ecosystem and nonflow-ecosystem variable interactions established in this assessment, 2) validate the hypothesized ecosystem structure and function used to represent the socioecological system considered in this assessment, and 3) verify the probable response of the socioecological system to change in flow and other variables if the recommendations are or are not implemented. It is projected that an improved regional balance between the use and protection of the water resources in the region can be obtained if these recommendations are implemented.

The holistic RRM-BN approach demonstrated in the present study allows for the evaluation of the socioecological consequences of multiple water quality and flow stressors associated with a range of resource use and protection scenarios. The approach can be used in other case studies to represent socioecological systems, and risk pathways from multiple sources, stressors, receptors, and endpoints that represent important resource use and protection attributes to contribute to the determination of sustainable balances between the use and protection of water resources.

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Open Data Badge—This article has earned an Open Data Badge for making publicly available the digitally shareable data necessary to reproduce the reported results. The data are available at https://figshare.com/authors/Jan_Hoinkis/8719386. Learn more about the Open Practices badges from the Center for Open Science: https://osf.io/tvyxz/wiki.

Data Availability Statement—The data that support the findings of this study are available from the Supplemental Data or from corresponding author Gordon C O'Brien (gordon.obrien@ump.ac.za) upon reasonable request.

SUPPLEMENTAL DATA

Figure SI-1. Average relative risk scores to the ecological endpoints, including the vegetation, fish, and macroinvertebrate components for each risk region assessed, with error bars representing standard deviation.

Figure SI-2. Average relative risk scores to the social endpoints, including natural products, recreation, water abstraction, and effluent assimilation components for each risk region assessed, with error bars representing standard deviation.

Figure SI-3. Average relative risk scores to the ecological endpoints, including the vegetation, fish, and macroinvertebrate components for site EWR18 during the high flow (A) and low flow (B) periods, with error bars representing standard deviation.

Figure SI-4. Average relative risk scores to the ecological endpoints, including the vegetation, fish, and macroinvertebrate components for site EMAN2 during the high flow (A) and low flow (B) periods, with error bars representing standard deviation.

Table SI-1. Average relative risk scores to the ecological endpoints considered in the risk assessment of water quality and quantity to the lower Thukela River, including the vegetation, fish, and macroinvertebrate components for each risk region assessed, with error bars representing standard deviation. These data were used to generate Figure SI-1 of the Supplemental Data

Table SI-2. Average relative risk scores to the social endpoints considered in the risk assessment of water quality and quantity to the lower Thukela River, including natural products, recreation, water abstraction, and effluent assimilation components for each risk region assessed, with error bars representing standard deviation. These data were used to generate Figure SI-2 of the Supplemental Data

Table SI-3. Average relative risk scores to the ecological endpoints considered in the risk assessment of water quality and quantity to the lower Thukela River, including the vegetation, fish, and macroinvertebrate components for site EWR18 during the high flow (A) and low flow (B) periods, with error bars representing standard deviation. These data were used to generate Figure SI-3 of the Supplemental Data

Table SI-4. Data used to parameterize the models for the risk assessment of the water quality and quantity to the lower Thukela River, including rank thresholds established to represent the socioecological system being evaluated in the study. The system variables or nodes (node names) selected for the models, network variable titles, ranks and associated modeling scores, rank definition and measures for variables, and justification for the use of the variables with evidence to describe their use in the risk assessment are provided with justification references.

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