



**SOURCE TO SEA:  
Tracing Causes of Water Quality Problems and Evaluating  
Potential Mitigation Options  
Case Study of uMngeni River, South Africa**

**Evaluating the Impact of Scenarios**

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# 1 Background

## 1.1 Objectives

This report summarizes efforts completed during bilateral collaboration “Source to Sea: tracing causes of water quality problems and evaluating potential mitigation options in uMngeni River, South Africa” between Sweden represented by SMHI and South Africa represented by University of KwaZulu-Natal and Durban University of Technology. This collaboration started in 2016 with an objective to produce advanced decision-support for efficient reduction of water pollution. The aim is to develop a Proof-of-Concept on how to produce advanced decision-support for efficient reduction of water pollution in the uMngeni River. The project is in support of the South African pilot studies on “Ecological Infrastructure” which is strategic initiative of the Department of Environmental under the Presidential Strategic Infrastructure Projects or SIP on Ecological Infrastructure for Water Security (known as SIP 19). The uMngeni catchment is a pilot site for this initiative and we work closely with Department of Environmental Affairs on this through SANBI (South African National Biodiversity Institute) and their Environmental Programmes Branch ([https://www.environment.gov.za/branches/environmental\\_programmes](https://www.environment.gov.za/branches/environmental_programmes)).

The “Source to Sea” case study of uMngeni River will provide a sustainable technical platform for water-quality assessments in South Africa, linking policy and water management. Main focus is current problems with nutrients and pathogens along the river. The assessment will consider potential measures with local acceptance, as well as climate change impact. The work during 2017 was mainly focused on closing the existing knowledge and data gaps identified during the first stage of the collaboration, refining the developed modelling system, and using the system to evaluate the impacts of various scenarios on water quality and water quality.

The greater uMngeni catchment is under severe stress to supply the demand. Water is already brought in from other near-by catchments to provide additional volume needed by the water users and additional transfer schemes are being implemented and/or considered. Drought conditions were experienced in 2014 and continued through 2016. Raw water quality issues exacerbate the situation.

Upstream of the Durban Bay the water reservoirs are eutrophic, mainly due to nutrient emissions from agricultural activities and scattered settlements. Agriculture causes effluents from livestock production as well as leaching of nutrients from crop growing areas. Erosion and sediment loss is an associated concern and there is thus need for a strong focus on impacts of land use in the upper part of catchment. Further downstream, the water quality issues are driven by sanitation and pollution problems from the cities of Pietermaritzburg and Durban.

The water quality in these urban areas close to the coast is affected by the insufficient and overloaded systems, causing emissions of pathogens and antibiotics to the water system. This has led to problems with using water for bathing and drinking.

This study utilizes the HYPE model <http://hype.sourceforge.net/> developed by the SMHI. The model can quantify the impact from various sources to polluted waterbodies and also distinguish between natural and anthropogenic influence. During 2016, the model was set up and calibrated for the uMngeni River basin and surrounding basins. During 2017, an increased understanding of important processes affecting water quality and quantity in the study region was obtained. This knowledge together with additional collected data was used to improve the model code and the model set-up for the study area. Doing so made the model system usable for assessing the effects on water quality and quantity of different water infrastructures, possible socio-economic pathways and various mitigation options for improved water resources.

## 1.2 Study Area Description

The uMngeni River catchment is 4000 km<sup>2</sup> (Figure 1) and managed as part of the water district 'Greater uMngeni' also including the Mooi and Mkomazi Rivers. They all have their origin in the KZN Drakensberg and its foothills, and are eastern flowing systems which drain into the Indian Ocean. Together they are utilized to provide water to the cities of Pietermaritzburg and Durban and surrounding areas.



Figure 1. Study area: uMngeni catchment and surrounding basins.

The uMngeni River catchment contains six major upstream dams and has one downstream estuary. The upper parts are characterized by timber production and agriculture (crops, soya and cattle), while the lower parts are more industrialized. At present, the region undergoes rapid urbanization with organically growing cities and it is part of the economically important Durban–Gauteng corridor for logistics and transport.

The three rivers have interbasin transfer schemes that are either in place or planned to augment supply in the uMngeni system. The uMngeni River mouth is just to the north of the City of Durban. Umgeni Water (UW) is the principal supplier of water to consumers in the catchment. The study area includes two Water Management Areas (WMAs). WMA 16 (Mvoti to Umzimkul) includes rivers Mvoti, Umgeni, Umkomazi, and Umzimkulu. WMA 13 represents the catchment of the Thukela River.

University of KwaZulu-Natal has developed a detail HYPE model for the upper part of uMngeni River catchment and ACRU model for uMngeni River catchment. The SMHI modeling efforts complement those of the partner universities. The SMHI model represents a larger area for direct evaluation of existing and potential future transfers and their impacts on water quantity and quality in uMngeni River as well as in the catchments where the transfers originate.

### 1.3 Water Management

Umgeni Water manages the twelve impoundments and one weir on three major systems. The Mgeni System utilizes four dams on the uMngeni River and Mooi-Mngeni Transfer Scheme (**Fel! Hittar inte referenskölla.**). The Mooi-Mngeni Transfer Scheme (MMTS) is being completed in several phases. Phase 1 augmented the capacity by 334 million m<sup>3</sup> per year (Umgeni Waters, 2016a). Phase 2A (completed in 2013) added 47 million m<sup>3</sup> per year. Phase 2B will add 13 million m<sup>3</sup> per year to a total of 394 million m<sup>3</sup> per year.

Table 1. Dams in Mgeni Water Resource System (after Umgeni Water, 2016a)

Catchment	Impoundment	Gross Capacity million m <sup>3</sup>
Mooi	Mearns Weir	5.1
Mooi	Spring Grove Dam	139.4
Mgeni	Midmar Dam	235.4
Mgeni	Albert Falls Dam	290.1
Mgeni	Nagle Dam	24.6
Mgeni	Inanda Dam	251.6
Mlazi	Shongweni Dam <sup>#</sup>	3.8
Msunduzi, Mgeni	Henley Dam <sup>#</sup>	1.5
<b>Total</b>		<b>951.5</b>

Current demands are slightly greater than the 99% assurance of supply level that will be achieved with completion of Phase 2B (Umgeni Waters, 2016a), indicating additional sources will be needed. The uMkhomazi Water Project is planned to transfer water from uMkhomazi River with a completion date in 2023. Additional alternate sources considered in the planning are wastewater reuse and seawater desalination.

As of December 7, 2016, most dams in the Mgeni system were at 45-65% capacity (Umgeni Water, 2016b). Albert Falls Dam, the largest dam in the system was at 27% capacity due to a lack of water in Midmar Dam and the consequent discontinuation of the transfer from Midmar to Albers Falls during the drought.

Raw water quality problems have been reported in 2010, 2012, and 2016 (Umgeni Water, 2010, 2012, and 2016a in Table 2). There appears to be a shift toward good and excellent water quality in the verbal description, although the recent description seems to be focusing more on the intake point rather than the whole impoundment.

Table 2. Water Quality in Mgeni Dams (after Umgeni Water, 2010, 2012, and 2016a)

Basin	Impoundment	Year	Raw Water Quality Problem
<b>Mooi, Mgeni</b>	Mearns Weir; Midmar Dam	2010	High algal counts associated with high nutrient concentrations, and iron and manganese problems have been experienced on occasion.
	(incl. Spring Grove Dam)	2012	Good water quality in Mgeni inflow. Eutrophication in Mthinzima stream inflow.
		2016	Excellent to good quality from the abstraction point in Midmar Dam. Occasional elevated nutrient concentrations in the inflow rivers to the impoundments as a result of inputs from the catchment. These results in elevated algal counts in the impoundments on a few occasions each year.
<b>Mgeni</b>	Albert Falls Dam	2010	High algal counts associated with high nutrient concentrations and high turbidity/suspended solids.
		2012	Excellent quality in Albert Falls dam, from where water is stored and released for abstraction in Nagle dam.
		2016	Excellent to good quality in Albert Falls Dam at the site from where water is released for abstraction downstream in Nagle Dam. Elevated nutrient concentrations in the inflow rivers to the impoundments as a result of inputs from the catchment, particularly from Howick WWW and problematic sewer infrastructure in that area.
	Nagle Dam	2010	High algal counts associated with high nutrient concentrations and high turbidity/suspended solids.
		2012	Occasional algal blooms in Nagle dam due to eutrophication in intermediate catchment (feedlots in Nagle dam catchment area).
		2016	Excellent to good quality from the abstraction points in Nagle Dam. Occasional elevated nutrient concentrations and turbidity problems in the inflow to the impoundment as a result of the catchment rain events.
	Inanda Dam	2010	Elevated algal counts, associated with high nutrient concentrations, chemical contamination and high suspended solids.
		2012	Good quality at the abstraction site, which is situated near the Inanda dam wall. Poor quality in upper reaches of the Dam, where there is high algal count from eutrophication and high organic carbon (arising from Msunduzi tributary, which drains Pietermaritzburg, and Darvill WWTW)
		2016	Excellent to good water quality from the abstraction point in Inanda Dam. Poor quality in upper reaches of the Dam due to high algal counts associated with nutrient enrichment from the Msunduzi catchment and Darvill WWTW.

## 2 Data and Methods

This project adapts an agile approach with incremental model development and responsive scenario analysis (Figure 2). This means that we started with available information and we will improve and refine the results in a step-wise manner, starting with the major inconsistencies and obvious errors and finishing with the minor tuning. Result analysis and model development will thus be performed in an interactive manner throughout the project period. The model development and data sources summarized below are described in greater detail in Model Documentation (SMHI, 2016).

The first round of preliminary results was presented in an earlier report (SMHI, 2017). This report describes the model results after the first iteration of model refinement and the results of scenario analyses. The most significant model refinements include updates to agriculture and crop management, pasture management, and new water transfer routine code and its implementation in the model. Model development is performed in collaboration with hydrological scientists from both countries. Scenarios were defined in collaboration between hydrologists, social scientists and local stakeholders during the SMHIs visit in the study area.

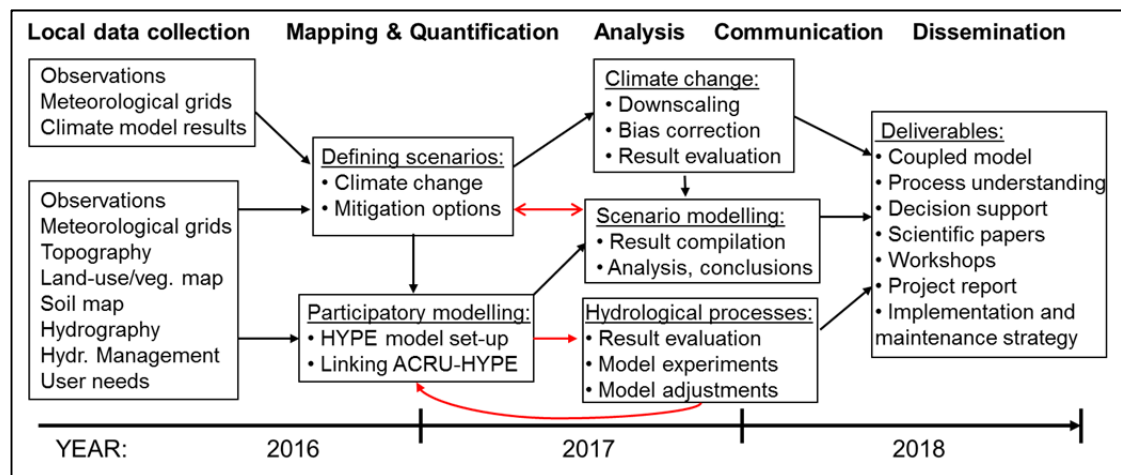


Figure 2. Project outline with tasks and timing over the proposed three years. Red lines indicate the agile interactions between result analysis and model/scenario development.

### 2.1 Model Development

#### 2.1.1 Data processing

This study uses HYPE model executed at a daily time-step. The study area is divided into 317 catchments with area ranging from 0.36 to 830 km<sup>2</sup>. The model results were evaluated for 1988-2013 for flow, inorganic nitrogen (IN), and soluble phosphorus (SP).

Catchment delineation was created by combining existing delineations from three sources: detail delineation of uMngeni River based on DWS quaternary catchments and adjusted by the University of KwaZulu-Natal during their development of the detail HYPE model. Each catchment is connected to the downstream catchment to form a hydrological network from source to sea.

Land use and soil information were combined to form so called Hydrological Response Units (HRUs), units of land that behave differently from hydrological perspective given the same meteorological forcing. Each catchment has a unique distribution of HRUs depending on what landuse and soil types or crops are present within the catchment.

The HYPE model has explicit routines for simulating lakes and regulated dams. Data on areas and depths of the most significant dams were used to be able to simulate these important hydrological features.

The most important water transfer schemes were also included in the model set-up. These include the water transfer from the Mooi River and water abstraction for drinking water from some of the major dams in the area. Data on the magnitude of the transfers is available as time series from the Department of Water and Sanitation. The water transfer was included in the model as yearly means using the new water transfer routine incorporated in HYPE code v.5.2.1.

Crop information was updated following advice from our partners at the University of KwaZulu-Natal. This information included estimates of timing and amount of fertilizer applications.

The contribution of nutrients to the watercourses from population sources (waste water) were estimated from population statistics, per capita coefficients of nutrient excretion and information on the locations and status of sewage treatment plants. Information on proportion of households with and without a flushing toilet was used to separate the load delivered through sewer systems to a waste water treatment facility and the load from informal settlements that is simulated as a high density rural source.

## **2.1.2 Calibration**

After the data were processed into the format compatible with HYPE, the model was calibrated to fit observed flows. Figure 3 show the locations of flow measurement stations, but several of the available stations were removed from the study due to problems with the quality of the data. The aim of the calibration was to achieve as good overall performance as possible in the area. Flows were calibrated first as having a good hydrological model is critical for obtaining a good water quality model.

Efforts were made during the calibration process to match the volumes and dynamics of the flow measurements at flow gauging stations in the area. This was mainly achieved by adjusting model parameters controlling the evapotranspiration from the various land uses and runoff characteristics of different soil types. Regulation routines for major dams were also introduced.

Calibration of water quality model parameters started after the completion of the water calibration. Again, the levels of riverine nutrient concentrations at the monitoring sites in the modelled area were optimized while trying to match the seasonal pattern of the observations. The model was optimized on inorganic nitrogen and soluble reactive phosphorus concentrations as these fractions of nitrogen and phosphorus are most often found in the observational data.



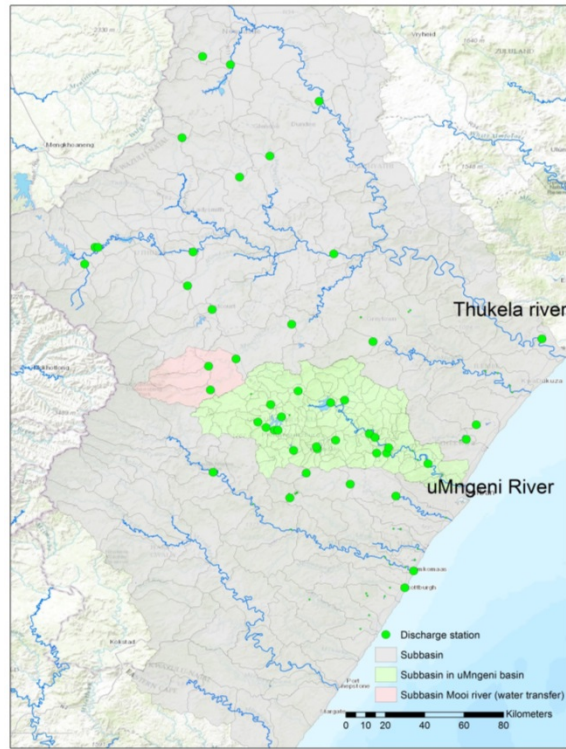


Figure 3. Locations of river discharge stations in the study area.

## 2.2 Data sources

Data sources were identified together with our partners from University of KwaZulu-Natal. Most data sources were national databases providing open data. A summary of input data used in the model set-up is found in Table 3.

Table 3. Summary of data used for the model set-up

<i>Characteristic/ Data type</i>	<i>Original dataset</i>	<i>Data Provider</i>
<b>Catchment delineation</b>	Quaternary catchments for South Africa	Department of Water and Sanitation (DWS)
	uMngeni catchment delienation	Umnjeni Water (bulk water supplier)
<b>Elevation</b>	HydroSheds	USGS
<b>Soil characteristics</b>	South African Atlas of Climatology and Agrohydrology	The Centre for Water Resources Research (CWRR)
<b>Land use characteristics</b>	National Land Cover 2013-2014	Department of Environmental Affairs
<b>Lakes and reservoirs</b>	Dam register	DWS Dam Safety Office (DSO)
<b>Discharge measurements</b>	Daily time series	Department of Water and Sanitation (DWS)
<b>Daily precipitation and temperature</b>	SMHI Global Forcing Data	SMHI
<b>River nutrient measurements</b>	Nitrogen and phosphorus concentration from river sampling programmes	Department of Water and Sanitation (DWS)
<b>Crops</b>	NLC2000	Agricultural Research Council, Council for Scientific and Industrial Research
<b>Water transfers</b>	Time series of daily flow though pipelines	Department of Water and Sanitation (DWS), uMngeni Water

### 2.3 HYPE code development

Water transfers play a major role in the Greater uMngeni area. Large amounts of water are moved between the basins to assure sufficient drinking water supply for the urban areas in lower uMngeni watershed. This affects both quantity and quality of water in the waterbody receiving the transfer as well as the waterbody that is providing the water. HYPE code v.4.12.2 used during the first year of this study (2016) lacked appropriate routines that would allow for simulation of the full impact of these water transfers on water quality. The transfer was approximated by specifying an abstraction at Mooi River and a point source discharge of the same amount to uMnegni River. This simulates water quantity very well. Water quality at Mooi River was also simulated very well. However, the concentrations at the water

discharged to uMngeni River were approximated as constants so the daily variability in nutrient concentrations at Mooi River and its impact on uMngeni River was not simulated properly.

An updated HYPE code v.5.2.1 became available in 2017. Model files for the study area were updated to match the new code requirements and the existing transfer routine was implemented using a new water transfer option available in HYPE. This option allows the user to specify a time series of water transfer demand, i.e., the amount of water that is to be withdrawn if available, and transfer the available amount to another catchment in the study area with the same concentrations that are simulated in the place of abstraction.

## 2.4 Coordinating with local stakeholders

In July of 2017 representatives from SMHI visited the study area. The purpose of the visit was to discuss the ongoing model development with experts in water quality modelling at the University of KwaZulu-Natal and meet with local stakeholders. Building on their expertise a few key aspects of the modelling were identified for model improvement.

The contacts were established with the following local stakeholders and institutions:

- uMngeni Ecological Infrastructure Partnership (UEIP): a partnership of national and local government, water management agencies, community organizations, and stakeholders.
- uMngeni Water: a state-owned water management institution
- Institute of Natural Resources: applied research organization involved in strategic and operational support for implementation programs
- University of Kwazulu-Natal: academic institution, provides data and technical information as well as contact with local stakeholders
- WESSA (the Wildlife and Environment Society of South Africa): environmental organisation implementing high-impact environmental, training and education initiatives

One of the main aspects discussed during the visit was the details of the local agricultural management practices in the study area, which vary significantly from agricultural practices in Europe or Sweden where HYPE was applied previously. Among others, management of multiple crops in a year and pasture management were identified as playing an important role in being able to quantify nutrient loads and concentrations.

uMngeni Water is the main bulk water supplier in the area and a key player for water quality and quantity related questions. They are also responsible for sewage treatment works. During a meeting with officers at the organization the model setup and the modeling results were presented. One important issue now implemented in the model that was discussed in detail was their strategies for operating the dams. Providing good sanitation for the fast growing population is a continuous challenge due to lack of infrastructure in informal settlements and a failing existing infrastructure in some areas. uMngeni Water also provided time series of water transfers and dam releases. There was also an interest in investigating the possibility of making the model operational for water resources planning.

## 2.5 Scenario modelling

The second purpose of the visit to the study area was to meet with local stakeholders and discuss their needs. The model is a tool that can help stakeholders make science-supported decisions in their sphere of management authority. The discussion has focused on the current issues they are facing in the resource management and on societal changes that can affect their decision making.

The following current issues and future scenarios (listed in no particular order) were identified as important:

1. High-intensity grazing: increased number of animals in the same area. (i.e. more manure, more erosion);
2. Population densification and more informal settlements due to urbanization: increase in population per year to cities that congregates in informal settlements with no or low-treatment of waste-water;
3. Inclusion of a new water transfer from Mkomazi River ;
4. Intensification of dairy and piggery farms: feedlots and their emissions are specifically included in the model at a higher density;
5. Changes in sanitation: both impact of more efficient urban waste-water treatment on one side and a complete institutional failure on the other side;
6. Climate change impact using an ensemble of climate model models;
7. The big flood – moving nutrients from the smaller farm dams to the larger systems;
8. Shifts to dry sanitation systems (unlikely in the short term but inevitable in the long term);
9. Reduced compliance and enforcement with respect to discharge of inorganic pollutants by industry.

Scenarios 1, 2, and 3 were fully defined and simulated during this year (2017). All scenarios were simulated using historical meteorological data (1988-2013). Additional scenarios will be simulated during the next stages of this study.

### **2.5.1 Intensified grazing**

An intensification of animal production in the region was identified by stakeholders as an increasing threat to the water quality in the region. Increased grazing may lead to higher losses of nutrients through higher inputs of nitrogen and phosphorus to the land and increased soil degradation and soil loss through erosion.

To illustrate the sensitivity of the waters in the study area to changes in grazing, the number of livestock per ha were doubled. The baseline assumption about the nutrient input from grazing animals come from average livestock density numbers for the region of KwaZulu-Natal (KwaZulu-Natal Department of Transport, 2005). The amount of nutrient input, calculated using estimates of nutrient in excreta for the baseline values, were doubled. In addition, soil cover was reduced to account for the increased grazing pressure and more soil damage due to threading. Note that this approach may not represent a realistic scenario. However, the results can give guidance to the managers in evaluating relative importance of intensified animal production.

### **2.5.2 Population densification/urbanization**

Two scenarios were formulated for the population densification, one based on Census 2011 statistics and one based on the population growth rate suggested by stakeholders. Census 2011 (Statistics South Africa, 2011) lists number of households connected to various levels of water and human waste services within Kwazulu-Natal for 1996, 2001, and 2011. Figure 4 shows one metric reported in the Census 2011, a proportion of households with a flush toilet. The change in the number of households with and without a flush toilet was calculated from 2001 to 2011. The first scenario (Scenario A) assumes the same rate of change for each reporting unit is going to continue for another 10 years. The second scenario (Scenario B) assumes the same rate of change for the number of households with a flush toilet as Scenario A but assumes a uniform 2% annual increase in the number of households without a flush toilet in the urban areas over 10 years. Urban areas were defined for this purpose as areas with a population density greater than 100 inhabitants per km<sup>2</sup>.

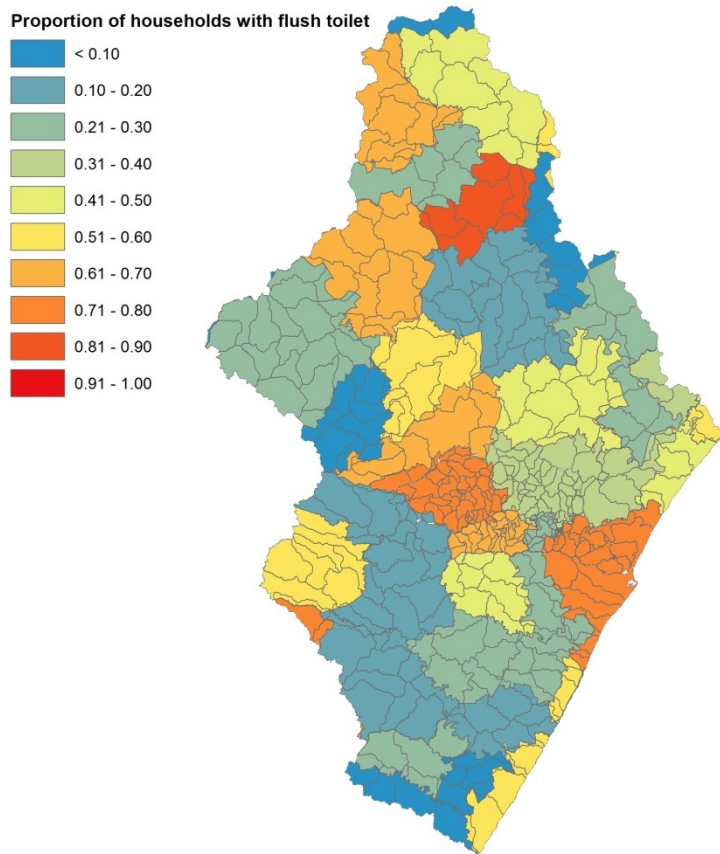


Figure 4. Proportion of households with flush toilets (Census 2011)

## 2.5.3 Water infrastructure

### 2.5.3.1 Mooi transfer

The purpose of this scenario is to evaluate the impact of the Mooi Mgeni Transfer Scheme Phase II (MMTS-2), the pumping of water from the Spring Grove Dam on the Mooi River to the uMngeni system. With the implementation of a new pump station immediately downstream of the dam (5.8 MW, maximum capacity of 4.5 m<sup>3</sup>/s), the capacity of the Mooi River to supply water will be fully utilized. The pumping will assure a continuous transfer of water throughout the year.

The impact of this transfer was evaluated in terms of changes in stream flows and nutrient concentrations both downstream of the water release in the uMngeni system and downstream of the water withdrawal from the Spring Grove dam in the Thugela system. The largest impact will be during the low flow season, which is why this evaluation was only done for the period June to September.

The implementation of the MMTS-2 in the model consisted of two parts. First, the dam itself had to be included in the model to account for the increased storage of the water in the stream system. Second, a continuous transfer of 3 m<sup>3</sup>/s was implemented, corresponding to 2/3 of the maximum pumping capacity. The pumped volume was held constant as long as water was available for the withdrawal.

### 2.5.3.2 Mkomazi transfer

The uMkhomazi Water Project (uMWP) is planned to transfer water from uMkhomzi River to uMlaza River for treatment and then to uMngeni Water service area for consumption (Figure 5). uMkhomazi is the third largest river in Kwazulu-Natal in terms of mean annual flow. The first phase of the planned uMWP would comprise: (1) A new dam at Smithfield on the uMkhomazi River near Richmond; (2) Water conveyance infrastructure (possibly including pipeline and/or tunnels) to a balancing dam at Baynesfield Dam or a similar in-stream dam; (3) A water treatment works in the uMlaza River valley; and (4) A gravity pipeline to the Umgeni Water bulk distribution reservoir system below the reservoir at Umlaas Road.

Phase one provides a 99% assured stochastic yield of about 220 million m<sup>3</sup>/year. Phase two of the uMWP may be implemented when needed, and will comprise the construction of a large dam at Impendle further upstream on the uMkhomazi River to release water to the downstream Smithfield Dam (DWA, 2017). Together, these developments have been identified as having a 99% assured stochastic yield of about 388 million m<sup>3</sup>/year. The scenario simulated with HYPE assumed annual withdrawal of 147 million m<sup>3</sup>/year, based on the projected capacity of the first phase of the project (uMngeni Water, 2011). This represents 2/3 of the stochastic yield of the first phase.

In order to reduce the complexity of the scenario, only the first phase of the project including the proposed Smithfield Dam was considered at this time. The effects on flow and water quality in the uMkhomazi river downstream of the Smithfield Dam were evaluated. The proposed Impendle Dam and Phase two of the Mkomazi transfer can be included in the next part of this study.

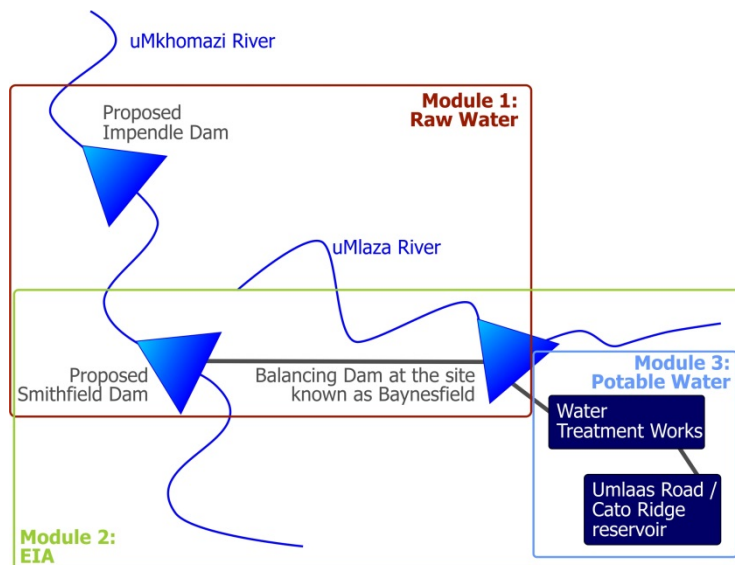


Figure 5. Schematic representation of the Mkomazi transfer (DWA, 2017)

## 2.6 Pollution source apportionment

HYPE model run can provide an apportionment of the different sources of pollution, both point and diffuse, for each subbasin. The model calculates how much each source type contributes to the total load in the subbasin. It is also possible to examine how much each upstream subbasin contributes to nutrient loads in a given basin. This is a function of gross load from different sources and retention processes in the river system. This analysis was carried out for inorganic nitrogen and soluble phosphorus.

### 3 Results

#### 3.1 Flow calibration

Much of the initial flow calibration was focused on minimizing the error between modelled and observed flow volumes at the flow gauging stations in the modelled area. Having accurate precipitation data is very important for good simulation of the stream flows, especially for the overall water budget and the evapotranspiration. Figure 6 shows spatial patterns of precipitation, evapotranspiration, and the resulting runoff from land to watercourses. The precipitation data come from the gridded Global Forcing Data (GFD) dataset developed at SMHI. The potential evapotranspiration was estimated using the Hargreaves-Samani method. This method was selected from the options available in HYPE after a thorough comparison of the methods performance in the study region

Flow volumes at the gauging stations are simulated generally well by the calibrated model (Figure 7), especially in the uMngeni-Mooi river basin. Here, the effort was focused on accurately representing the water transfers and abstractions in the model.

The dynamics of the simulated flow is generally in accordance with the flow observed at the monitoring stations (Figure 8), especially the seasonal pattern. Absolute values of the peak flows are not always well simulated. There is however a significant issue with the reliability of the observed data at many of the gauging sites that was confirmed during discussions with our local partners. This pattern is illustrated in Figure 9 for the most downstream flow monitoring station in the uMngeni River where the seasonality and the general dynamics of the flow are well captured but the observed flow peaks are often either underestimated or overestimated.

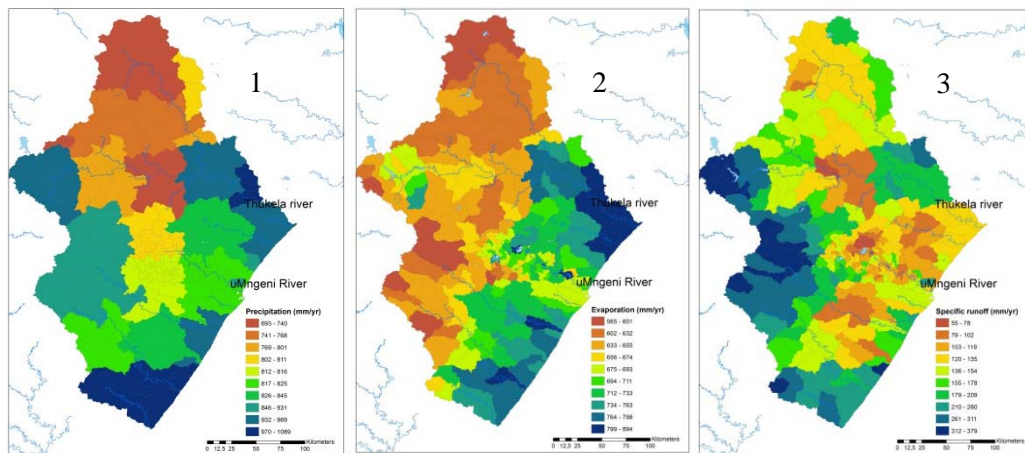


Figure 6. Maps of yearly 1- precipitation, 2- modelled evapotranspiration, and 3- modelled specific runoff in the study area.

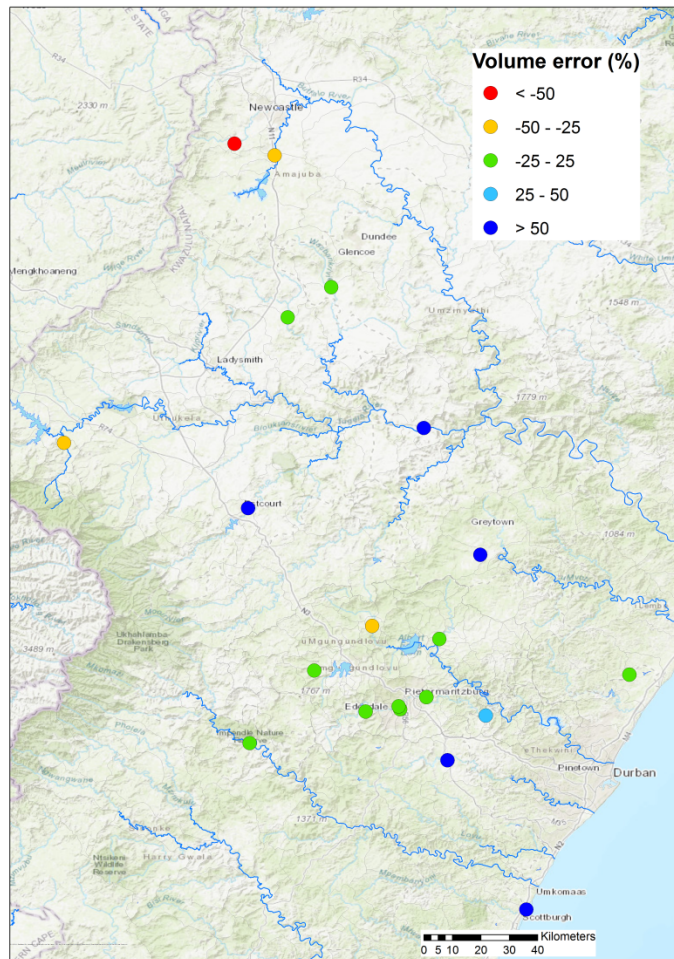


Figure 7. Error in simulated flow compared to observed flow at monitoring stations in the modelled area. The closer the error value is to zero, the better the model performs.



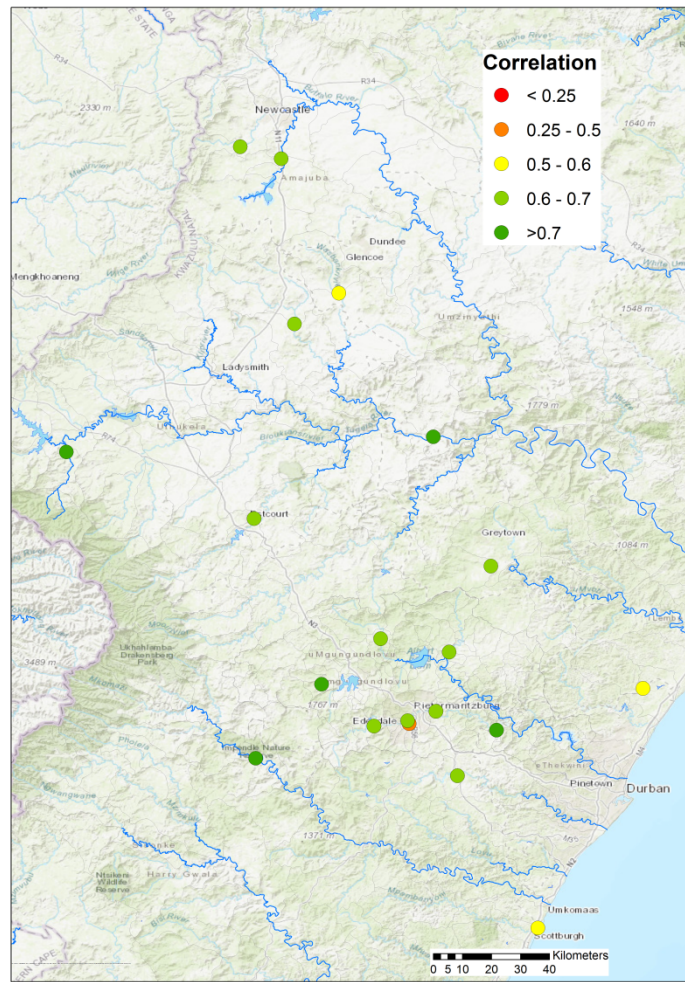


Figure 8. Correlation between simulated and observed flow at monitoring stations in the modelled area. The higher the correlation value, the better the model performs.

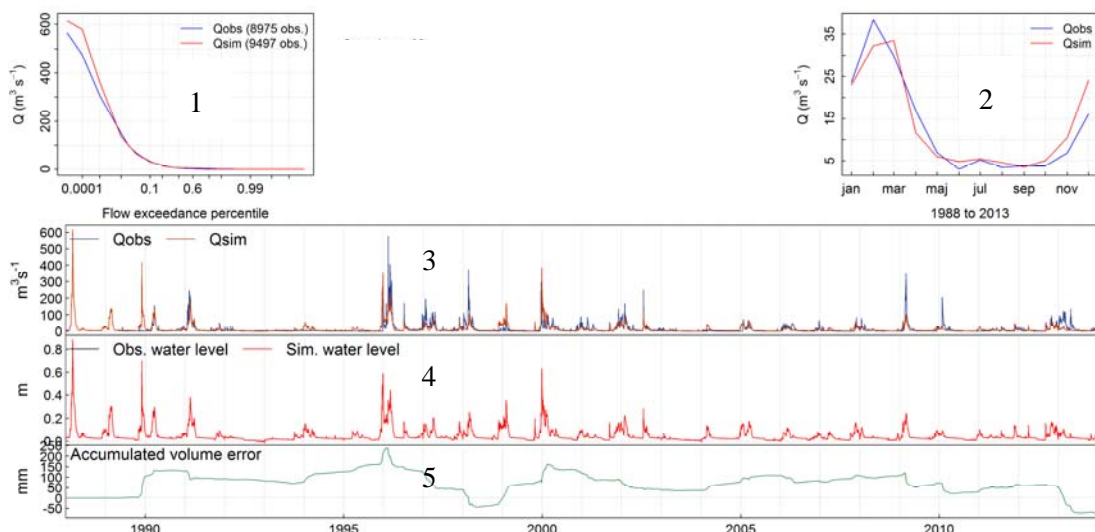


Figure 9. Evaluation of flow simulations at flow gauging station at the Inanda Dam on the uMgeni river. 1- Flow exceedance, 2- Monthly mean, 3- River discharge, 4- Water level in the Inanda dam, 5- Accumulated volume error.





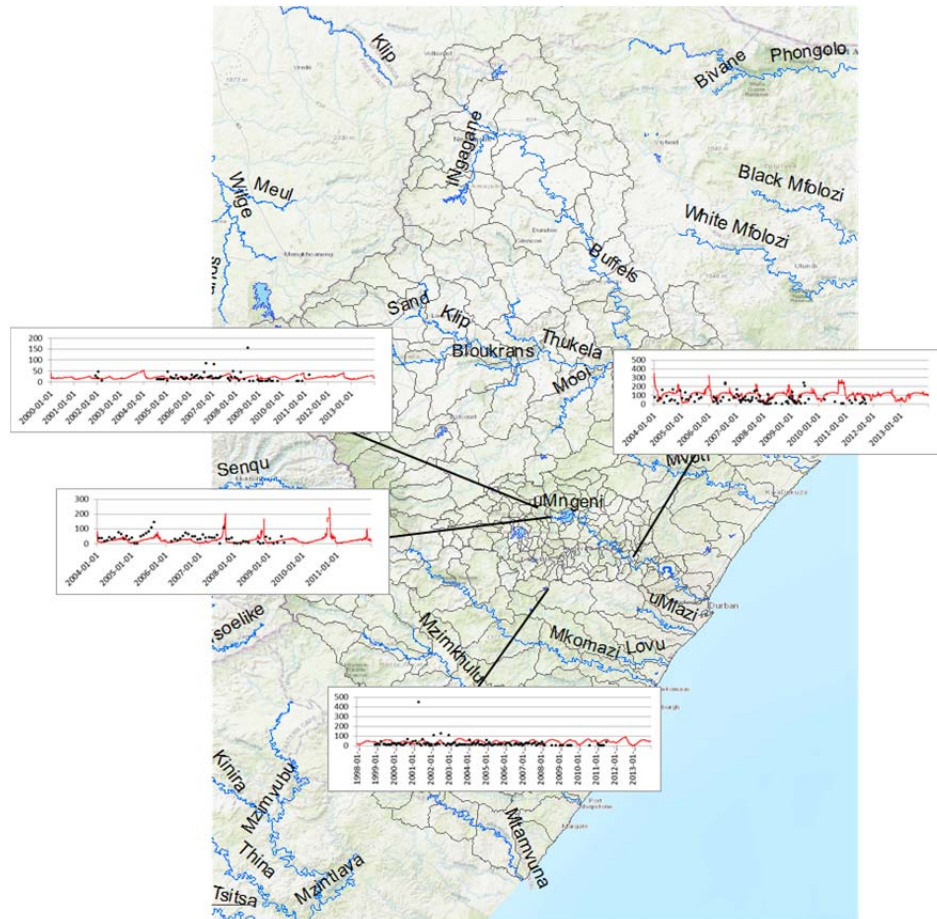


Figure 13. Example of simulation (red line) of soluble reactive phosphorus concentrations at some locations in the study area compared to observations (black dots).

### 3.3 Source apportionment

The contribution of various sources to the load of nutrients varies between rivers (Figure 14). Waste water contributes significantly to the nutrients transported to the sea. Grasslands are important in the Thugela and the uMkhomazi rivers. Leaching from cultivated land has a significant impact on the total load in Mvoti.

Nutrient transport at the lower reaches of the uMgeni River is dominated by waste water from rural and urban communities. The larger dams in the area act as traps for nutrients and very little of the nutrients from upstream of the Albert Falls dam reach the outlet (Figure 15). Percentage contribution to the transport of inorganic nitrogen (upper) and soluble reactive phosphorus (lower) in the uMgeni River (at Inanda Dam) from each of the different upstream subbasins of the river basin (Figure 15). Note that the percent contribution is partly driven by the catchment area; the larger the catchment, the larger the contribution from the same sources.

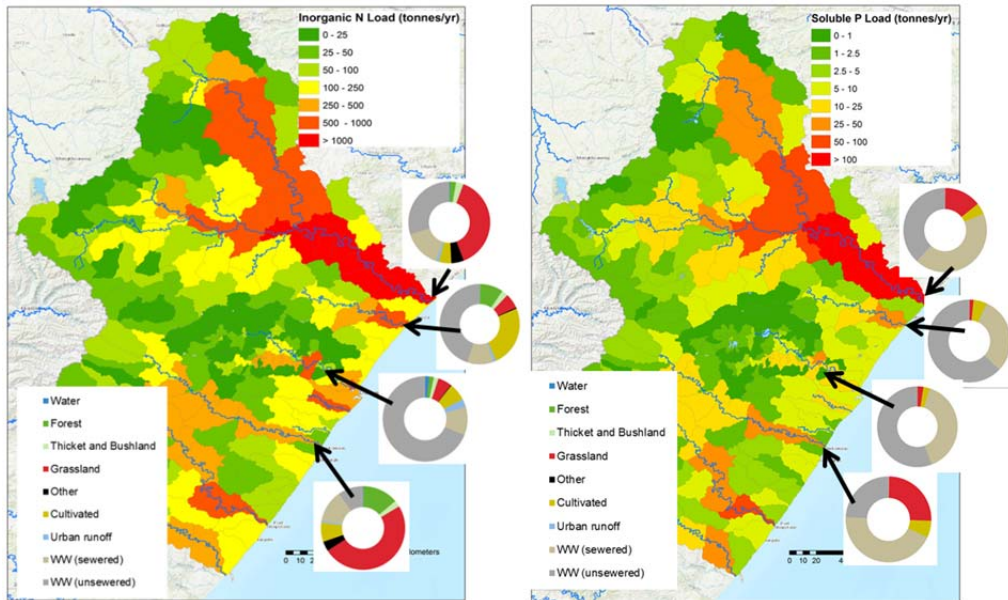


Figure 14. Transport of inorganic nitrogen at the outlet of subbasins in the area and source apportionment for four selected rivers (From top: Thugela, Mvoti, uMngeni (@ Inanda Dam) and uMkhomazi)

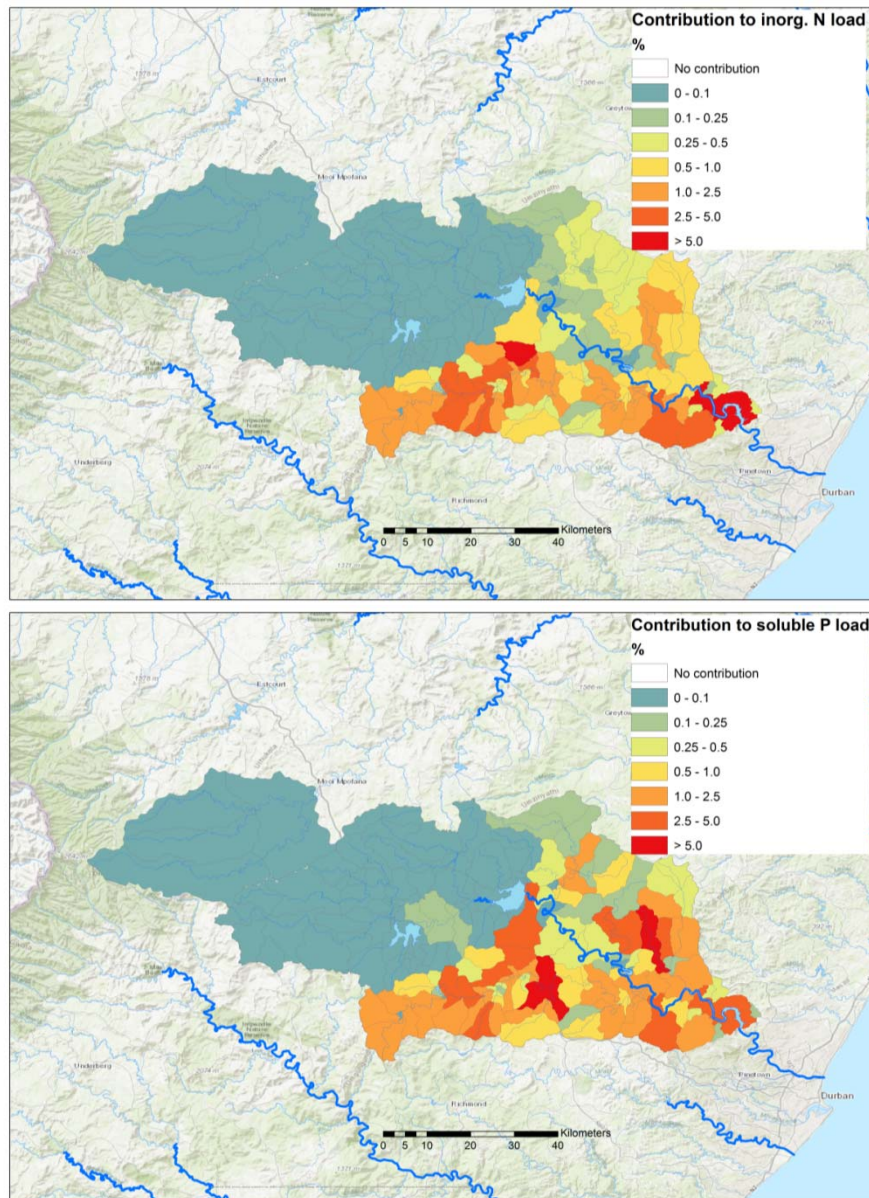


Figure 15. Percentage contribution to the transport of inorganic nitrogen (upper) and soluble reactive phosphorus (lower) in the uMngeni River (at Inanda Dam) from each of the different upstream subbasins of the river basin.

### 3.4 Scenario simulations

#### 3.4.1 Intensified grazing

The increased number of grazing animals results in a significant increase in nutrient concentrations (Figure 16). The relative changes are the highest towards the headwater catchments where grassland is dominating over other diffuse and human sources. In some of the main rivers in the study area, for example the Thugela and the uMkhomazi where grassland is an important nutrient source (compare Figure 14), the effect is seen all the way to the river outlet to the sea.

Most of the increase in total phosphorus is due to higher losses of particulate phosphorus associated with eroded sediments. Although little focus has been on calibrating total phosphorus, it is important to present these results for evaluation.

It should be noted that this scenario represents a rather extreme case with a doubling of the number of livestock in the area and a related increase in erosion due to the overgrazing. These modelling assumptions need to be considered when interpreting the results presented here.

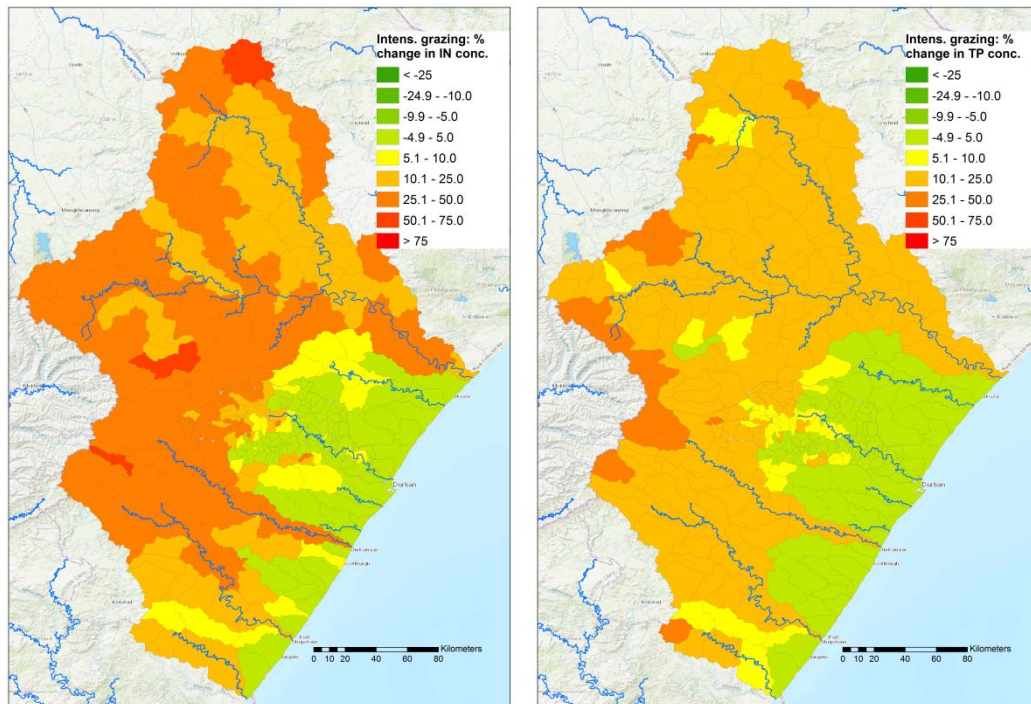


Figure 16. Relative changes in simulated riverine inorganic nitrogen and total phosphorus concentrations at the outlet of subbasins in the study area due to intensified livestock farming.

### 3.4.2 Water infrastructure

#### 3.4.2.1 Mooi Mgeni Transfer Scheme Phase II (MMTS-2)

The MMTS-2 transfers water from Mooi River to uMgeni River. Correspondingly, it will result in an increase of the base flow in the catchments downstream of the release in uMgeni (Figure 17). The relative increase in streamflow during the low flow season is largest in a catchment closest to the release point but can also be seen in river reaches further downstream (Figure 18). An opposite effect is seen in the Mooi River and Thugela River.

The nutrient concentrations in the uMgeni River are lower with the transfer in place than without it. The opposite is seen in the Mooi and Thugela. Relatively clean water from the Spring Grove Dam dilutes the discharges from point sources and improves water quality in the uMgeni. In the Thugela, less water is available for dilution due to the decreased base flow.

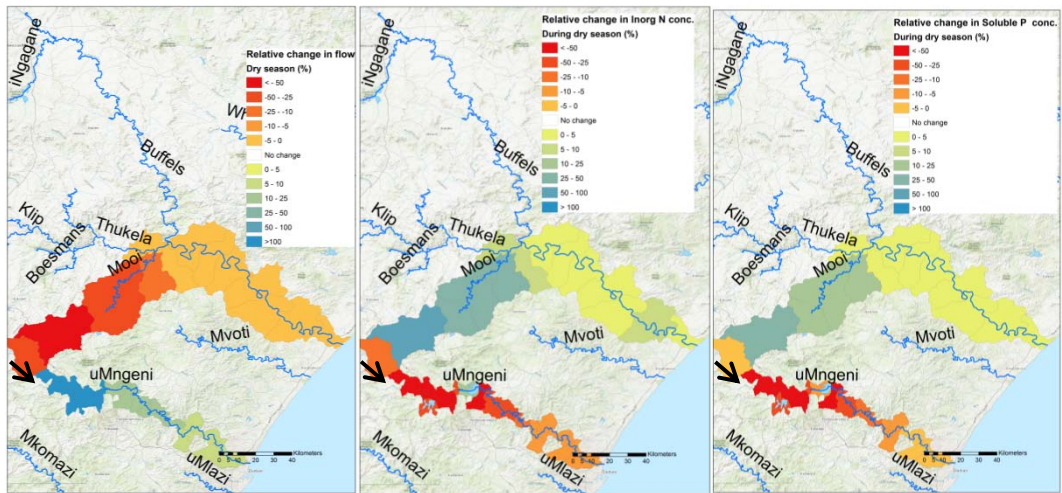


Figure 17. Changes in average stream flow and inorganic nitrogen and soluble reactive phosphorus concentrations at the outlet of the catchments in the model set-up during the low flow season (June-September). A comparison between the situation with and without the MMTS-. The arrow indicates the location of the transfer.

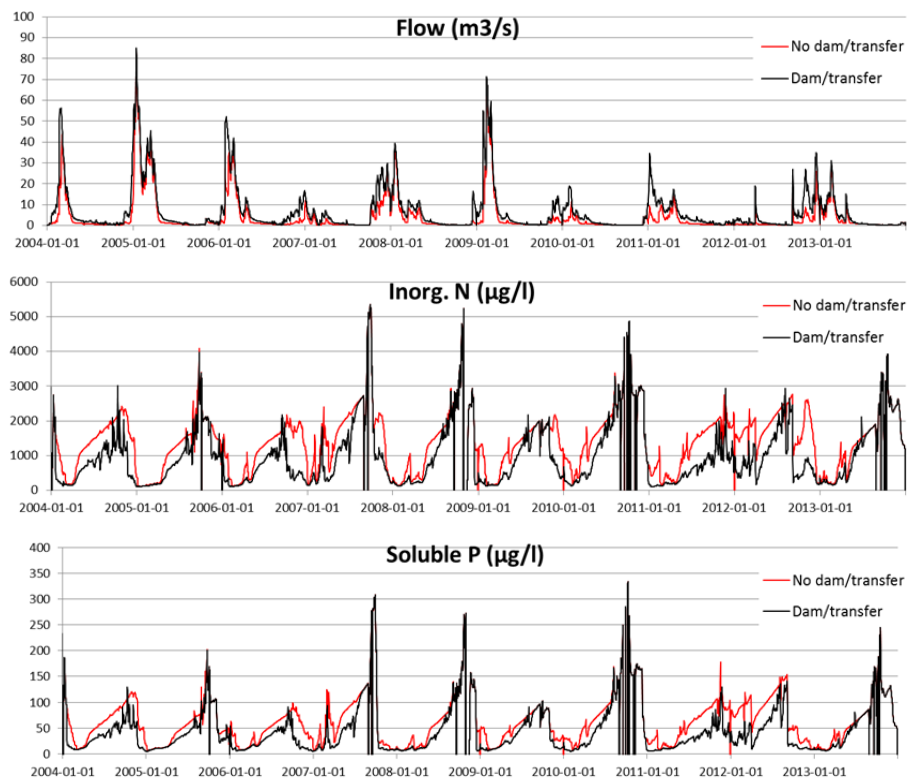


Figure 18. Simulated streamflow (upper), inorganic nitrogen concentration (middle), and soluble reactive phosphorus concentration at the inflow to the Albert Falls Dam. A comparison between the situation with and without the MMTS-2.

### 3.4.2.2 Mkomazi transfer

The proposed Smithfield dam on the uMkomazi River has a profound influence both on streamflow and water quality downstream of the dam (Figure 19). The baseflow is slightly higher with the transfer in place compared to the baseline, whereas some of the early streamflow peaks in the beginning of the wet period are missing. However, there are large uncertainties how the proposed dam will be operated after its construction so the actual effects may differ.



Construction of the dams typically results in decreasing nutrient concentrations mostly due to increased sedimentation and denitrification behind the dam. This is also observed for Mkomazi transfer, especially inorganic nitrogen concentrations are significantly reduced (Figure 19). The turn-over time for nutrients will increase dramatically with the dam resulting in increased retention.

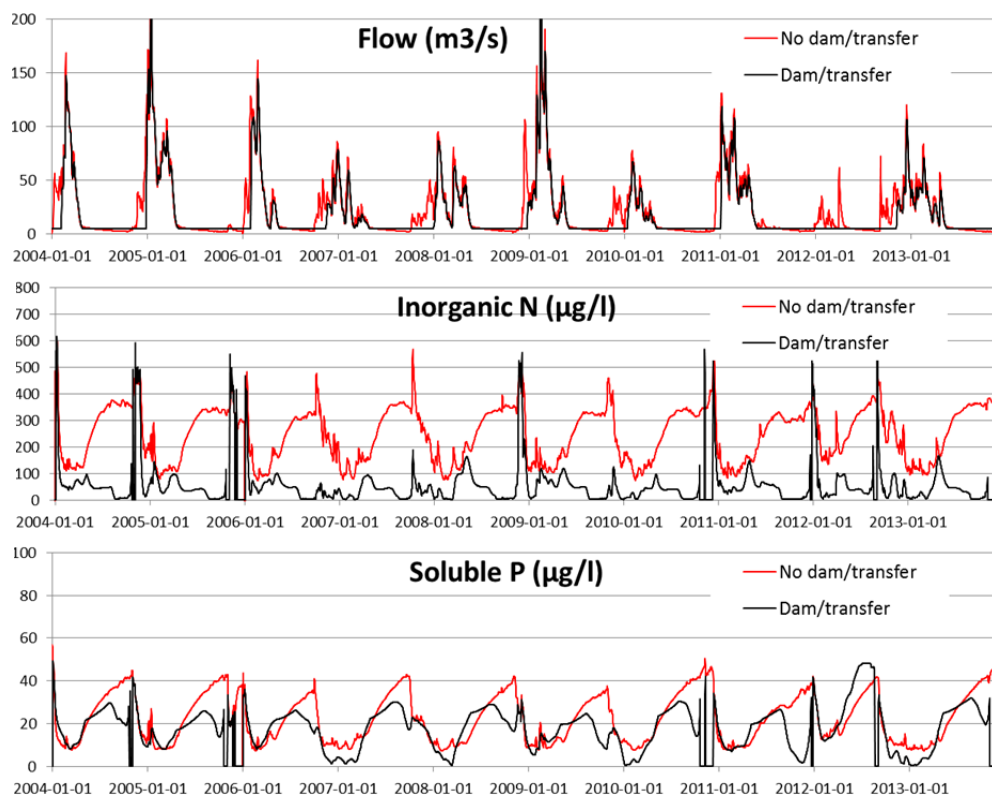


Figure 19. Simulated streamflow (upper), inorganic nitrogen concentration (middle), and soluble reactive phosphorus concentration immediately downstream of the proposed Smithfield dam on the uMkhomazi River compared to the situation without the dam.

### 3.4.3 Population densification/urbanization

Population densification has a significant effect on nutrient concentrations in developing urban areas (Figure 20 and Figure 21). It affects most major rivers in the simulated area, especially within the existing urban centers. Both treated and untreated waste water affects water quality mostly during lower flows. The stream flow changed slightly for both scenarios but not in a significant way. The change in concentrations is significant for both Scenarios. However, the impact is higher for Scenario B in many catchments.

Figure 22 shows an example of how population densification affected stream flow, inorganic nitrogen concentration, and soluble phosphorus concentrations at a catchment near the outlet of Thugela River to the sea. There are only insignificant differences in stream flows. However, the increase in nutrient concentrations is rather dramatic. The average inorganic nitrogen concentration has increased by 49% and 68% for Scenario A and Scenario B, respectively, at this location. The average soluble phosphorus concentration has increased by 110% and 165% for Scenario A and Scenario B, respectively, at this location.

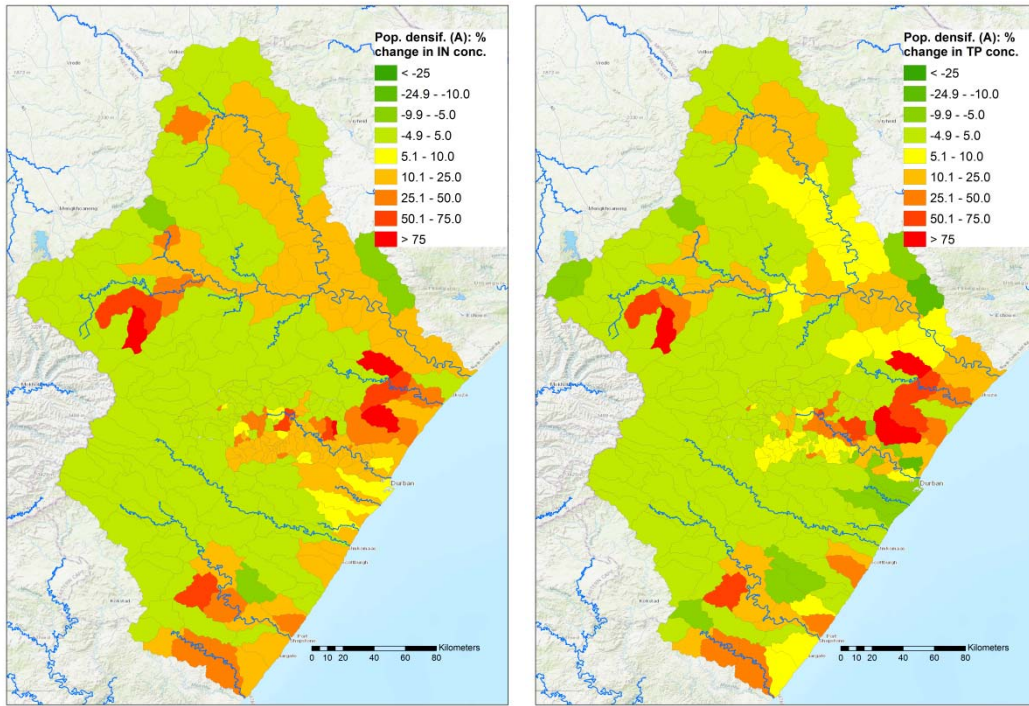


Figure 20. Relative changes in simulated riverine inorganic nitrogen and total phosphorus concentrations at the outlet of catchments in the study area due to the population densification following current trends in population and wastewater (Scenario A)

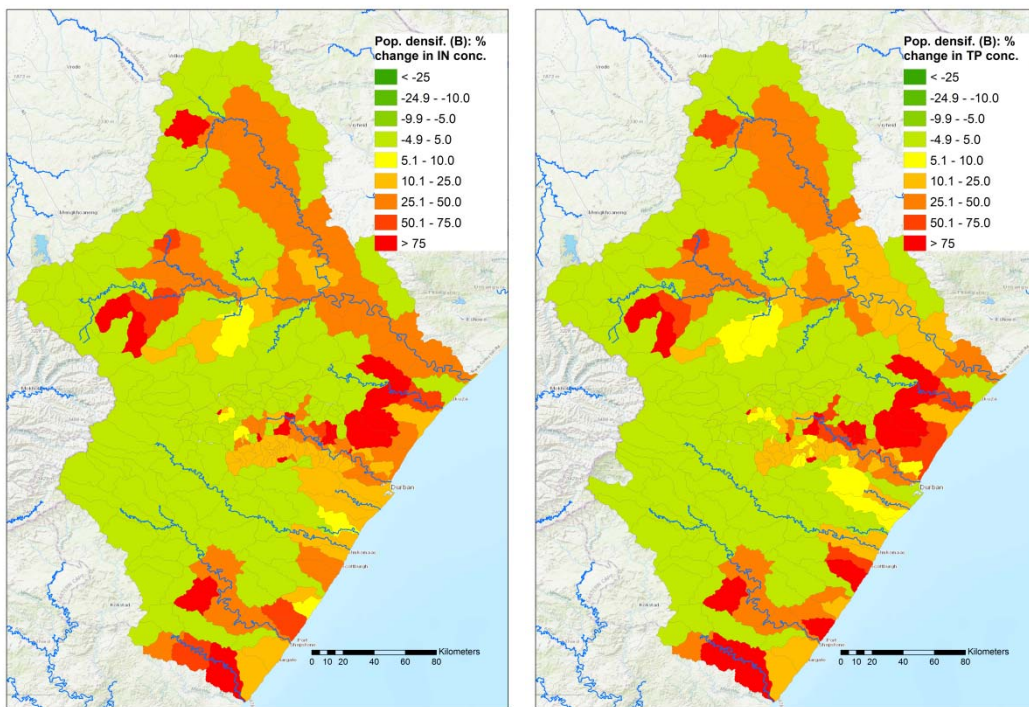


Figure 21. Relative changes in simulated riverine inorganic nitrogen and total phosphorus concentrations at the outlet of catchments in the study area due to the population densification assuming current trends in population with flush toilets and 2% increase in population without flush toilets (Scenario B)

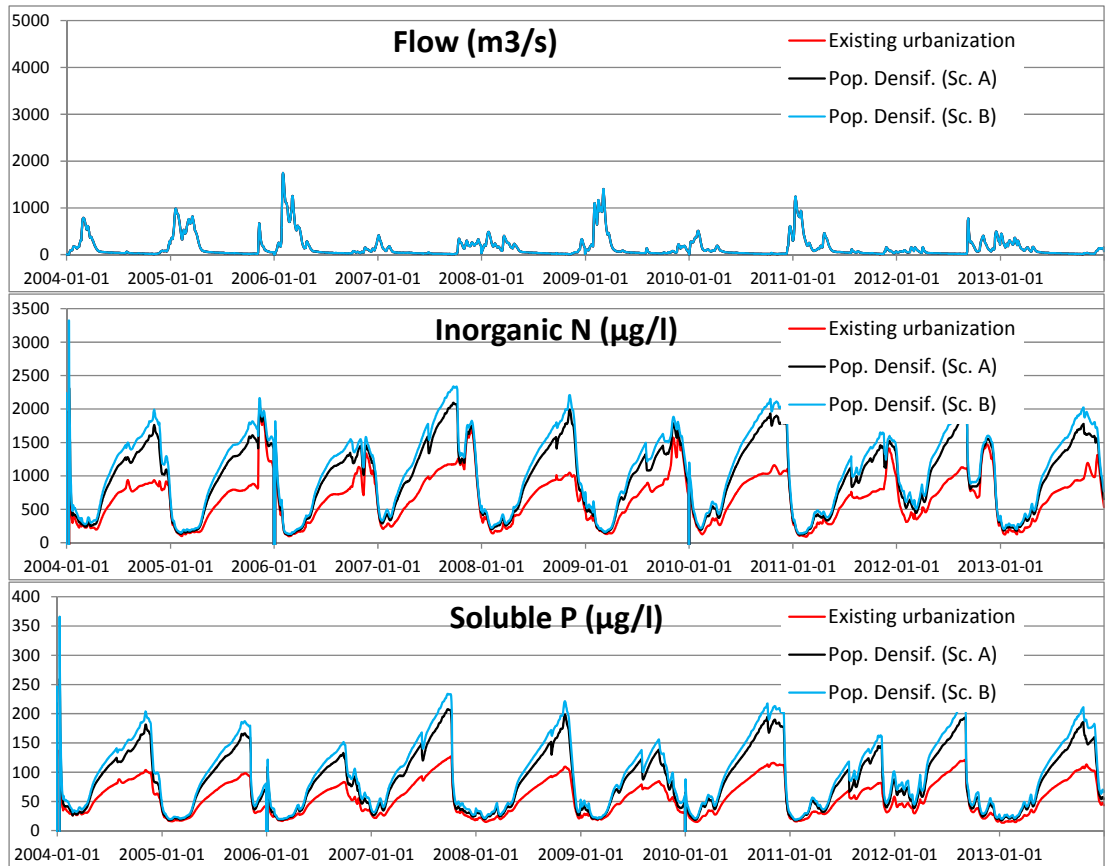


Figure 22. Simulated streamflow (upper), inorganic nitrogen concentration (middle), and soluble reactive phosphorus concentration at an outlet of Thugela River for the existing urbanization and Scenarios A and B.

## 4 Summary and next steps

The report has illustrated some of the possibilities of the modelling system to simulate processes that determine stream flows and nutrient concentrations as well as various user defined scenarios. The HYPE model has been successfully executed in the specific conditions of South Africa. The achievements can be summarized as follows:

- Well-performing hydrologic model (HYPE) simulating water quality and flows in the larger water management area of uMngeni developed with agile approach;
- Impact of the existing water transfer on water quality evaluated;
- Three potential development scenarios, namely intensified grazing, population densification, and planned water transfers evaluated;
- Preliminary results presented at the International Association of Hydrological Sciences Conference in Port Elizabeth (July 2017);
- Visited our partner, University of Kwazulu-Natal (July 2017);
- Established contacts with stakeholders in the study area (July 2017), discussed their needs and agreed on what future scenarios should be evaluated with the model;
- Two representatives from University of Kwazulu-Natal attended training course for HYPE in Norrköping (September 2017).

The scenarios were selected after meetings with local stakeholders. The study set up and results were positively received. The stakeholders expressed interest in several additional scenarios, including the effect of climate change on water quality and quantity. These additional scenarios should be considered in the upcoming stage of the study. There are some uncertainties in how the scenarios are implemented within the modeling environment. Follow up discussion with stakeholders are needed to refine the assumptions and definitions with local knowledge.

The overall promising result of the modelling is the demonstrated capability of the model to simulate water resource related indicators over a large geographic area in South Africa with a high spatial resolution. While there is always room for model refinements, this indicates that the current modelling efforts may be expanded further to cover other geographic areas and other environmental variables of interest to users. The main effort in the upcoming phase of the project should include:

- Continued refinement of the model calibration;
- Simulation of scenarios that are of interest to stakeholders, including feedback on the modeling assumptions;
- Climate change impact analysis, using an ensemble of Global Circulation Models;
- Expanding the model set-up to national coverage;
- Include new substances of interest to water managers, more specifically salinity, suspended sediments, and waterborne pathogens;
- Story mapping of Source-to-Sea evaluation along most affected rivers;
- Continued collaboration with partners in South Africa.

The collaboration with existing partners and in newly formed partnership with South African experts in relevant scientific fields is essential for this study to be successful. It is important to work along the existing studies in the area as well as to provide appropriate information to water resource managers there. We have established good functioning relationships with key local stakeholders

Analysis presented in this report give guidance on how operational water-management decisions affect water quality downstream, and how different societal sectors contribute nutrients transported from their sources to sea.

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