WATERQ2: UNDERSTANDING WATER QUALITY & QUANTITY IN THE LIMPOPO BASIN

Quarterly Report, 01 January – 31 March 2020

11 May 2020, version 1

Milestone #9

DISCLAIMER: This work was supported by the United States Agency for International Development (USAID), Southern Africa Regional Mission, Fixed Amount Award 72067419FA00001. This work reflects the work of the authors and does not necessarily reflect the views of USAID or the United States Government.

WaterQ2: Understanding Water Quality and Quantity in the Limpopo Basin

Suggested citation:

Kahler, D. M., Edokpayi, J. N., Rose, K. C., (2020). WaterQ2: Understanding Water Quality and Quantity in the Limpopo Basin, Quarterly Report, 01 January-31 March 2020. Thohoyandou, South Africa: Limpopo Resilience Lab.

Cover photo: Zebra, Kruger National Park, photo credit: Mackenzie Martin.

TABLE OF CONTENTS

Project Information

Project Title	Water Q2: Understanding Water Quality and Quantity in the Limpopo Basin
Geographic Locations	Botswana, Mozambique, South Africa, and Zimbabwe
Award Number	72067419FA00001
Implementation Dates	March 2019 to March 2022

Prepared for:

Akinwale Aboyade Agreement Officer's Technical Representative USAID/Southern Africa	Graham Paul Alternate Agreement Officer's Technical Representative USAID/Southern Africa

INTRODUCTION

The transboundary Limpopo River Basin crosses Botswana, Mozambique, South Africa, and Zimbabwe. At over 400,000 km^2, the Limpopo River Basin is home to 18 million people living in both rural and urban areas. Industries in the Basin include businesses in the urban areas and water-intensive uses such as agriculture and mining; industrial water use is growing rapidly. In addition to the human residents, the Basin contains some of the most biodiverse natural areas on the planet.

The rainfall in the Basin is heterogeneous with some sub-basins receiving less than 400 mm on average and other downstream sub-basins in Mozambique receiving over 750 mm annually. Even meteorological stations located in close proximity demonstrate substantial spatial variation within sub-basins. The Basin has experienced severe droughts in the last decade. In addition to the variation in the amount of rainfall, the timing, especially the start of the growing season, has varied significantly. However, there remain many questions about the reliability of rainfall data and other water measurements due in part to the infrequent calibration and validation of field site measurements. **The limited confidence in these data, combined with the substantial variation through time and space necessitates an integrated approach to improve data collection, validation, and overall Basin water resource management in the Basin**.

The goal of this project is to build resilience through the support of Basin stakeholders, including The Limpopo Watercourse Commission (LIMCOM), to improve governance around water resources management and water security in the Basin. A systems approach, such as integrated water resources management (IWRM) is needed to address such complex, large, and interrelated components of water resources. IRWM is recommended by the United States Agency for International Development (USAID) Water and Development Strategy Implementation Guide (2014). This context will be combined with data collection and validation, data sharing, and continuous evaluation of the interrelations that affect water resources.

This project will support water resources monitoring, and the development of methods for water quality and quantity measurement based on *in situ* sensors and satellite measurements. These **measurements** will enable characterization of water resource dynamics at the whole Basin scale and form the foundation for hydrologic **modeling** that can help estimate hard-to-measure parameters and also provide holistic assessments of Basin scale stocks and flows. To support data sharing, the project will use cloud-based, automated data collection and web-based **data sharing**.

The Development of local capacity to maintain water resources and make proactive, scientifically justified management decisions requires a substantial human capital resource that is currently lacking in the Basin. The project will provide training, workshops, and conferences will focus on integrated water resources management (IWRM) and environmental flow analysis.

The results of the water resources and biodiversity studies conducted will be compiled into a report for the Basin stakeholders. Continued high-quality data collection, training, and general logistics depends on dependable physical infrastructure. To support data collection efforts as well as training and collaboration the Limpopo Resilience Lab at the University of Venda will be established. The sustainability of lab activity will continue with the implementation of a small user fee beyond the duration of the project. Annual training workshops and conferences will be located at or nearby the Resilience Lab.

In this report, the collaborators, Duquesne University (Duquesne), University of Venda (Univen), and Rensselaer Polytechnic Institute (RPI) report their activities and progress in the fourth quarter (Q4) of project year 2019-20 (PY 2019-20).

PROJECT ADMINISTRATION

PROGRESS TOWARDS MILESTONES

Student research has continued during this quarter under the supervision of the PIs. The specific projects will be reported within the module which they support. The quarter began with continued fieldwork in January. All staff visited field sites in the Soutpansburg mountains and met with other collaborators. Staff also held meetings with CSIR and the South African Department of Water and Sanitation to support citizen science in the Limpopo Basin.

STAFFING

As this academic year ends, one of our Graduate Research Assistants (GRA), Mr. Sharp, will graduate and continue on with his education. Duquesne University has solicited applications for the graduate program and selected a GRA for the next two academic years, Sophia Bakar, whose resume is included in Appendix A. Ms. Bakar will commence work on groundwater investigations in the Basin.

COVID-19 PLANS

As the quarter draws to an end, the world continues to confront issues related to Covid-19 (also, SARS-Cov-2). This pandemic presents unique challenges to this program as many of the researchers are located in the United States and cannot travel, and South Africa is on lockdown and University of Venda is closed, under national directive. During this quarter, several research activities continued uninterrupted; specifically, research staff is able to continue work related to remote sensing and the measurement of flow in rivers, land classification and land use changes, and hydrologic modeling in key watersheds.

On 25 March 2020, a letter was sent to the Agreement Officer Representative that outlined out immediate plans and concerns regarding Covid-19 (Box 1). This letter, in large part, continues to be the understanding of the PIs at the close of the fourth project-year-quarter with some additional delays as outlined in this section. During the drafting of this report, the conditions around the world have continued to evolve and present unique and troubling circumstances for the project team. It is prudent that these concerns are presented in this report as well. We anxiously await official permission to extend our remaining milestones by three-months and the performance period of the grant by six-months. This would give the grant a period that ends 30 September 2022.

Given that South Africa has closed its borders to non-emergency travel, we anticipate that there may be some additional delays; however, we are unsure of those delays at this time. We also anticipate that there may be some additional cost due to these delays as the scientists may not be able to complete their work within the performance period. Specifically, we expect these delays to reduce our ability to conduct groundwater monitoring, which was scheduled for this summer. Our initial plan was to conduct groundwater monitoring throughout the project; however, due to delays with shipping instruments Covid-19, this cannot continue at this time. We will restart monitoring as soon as travel within South Africa is permitted. We will then start monitoring groundwater in other countries as travel restrictions are relaxed.

University of Venda (Univen) is currently closed and staff in South Africa are working remotely. Outside of major urban centers, internet connectivity is severely limited. Unfortunately, this has significantly reduced our communications with staff at Univen.

25 March 2020

Akinwale Aboyade
Agreement Officer's Representative
USAID/Southern Africa
100 Totius Street
Groenkloof 0027
Pretoria, South Africa

Dear Wale and Caroline:

The situation surrounding COVID-19 has been rapidly developing. In Pennsylvania, on 19 March, the Governor closed all non-life-sustaining businesses. In New York, the Governor closed all universities. In South Africa, following President Ramaphosa's emergency declaration on 15 March, all universities were to close last week; students are actively moving out of the University of Venda.

Luckily, with internet connectivity, many of our research functions such as remote sensing analysis and modeling are continuing; however, fieldwork has been abruptly halted. This causes a significant disruption to our productivity. Due to our inability to travel (even within South Africa), **I request that the performance period of this award be extended by six (6) months, to 30 September 2022 and all milestones, with the exception of the annual work plan, be extended by three (3) months**. This would not, at this time, add any additional funds.

Currently, all research staff are conducting work with remote access. Duquesne University and Rensselaer Polytechnic Institute will continue to pay salaries for research staff. University of Venda is subject to South Africa's shutdown tomorrow and they have not announced their plans for salaries. We expect that if these precautions end with the end of this semester, around May, the disruption to our ongoing monitoring will be minimal. If, on the other hand, travel restrictions persist, those working on fieldwork-intensive projects, including Hilton Shimbabu at University of Venda, and the incoming graduate student at Duquesne, may be significantly delayed. If this occurs, we may submit a request for some additional funds; please provide guidance on how you would like such a request if possible.

Sincerely,

David M. Kahler

Box 1: Copy of letter to AOR

IMPLICATIONS ON PLANNING

Due to Covid-19 restrictions, there have been some necessary changes. Specifically:

- Delays on data collection due to travel restrictions (Module 1)
- Delays on data collection as Kruger National Park is closed (Module 1)
- Conference has been delayed significantly (Module 2, Milestone #11)
- Training has been put on temporary hold (Module 2, Milestone #14)
- Delay of presentation of the first version of the basin report (Module 3, Milestone #12)

Each of these delays and the proposed response to each is listed within the respective module.

MODULE 1: WATER MONITORING

HYDROMETEOROLOGICAL STATION NETWORK

Data from stations established in this project continue to be monitored and uploaded to the Development Data Library, (DDL, data.usaid.gov). Data are available directly from the DDL and linked from the project website. We requested that the data are publicly available in September 2019 and are currently awaiting approval. The project website traffic is summarized in Appendix B. There were plans to continue hydrometeorological station installation in June 2020 in Botswana; however, due to Covid-19, those plans have been suspended.

REMOTE SENSING OF RIVER QUANTITY

Research staff has continued to obtain data from Planet Labs satellites for discharge research and water quality, and from Landsat for water quality through Planet Labs' Education and Research Program. Ms. Martin has made progress on an algorithm to identify the edge of water values in a given Planet Labs image and measure the width of a river along a transect perpendicular to the mean flow. The algorithm is being developed in the open source platform, R, and will be released publicly following testing and peer-review.

REMOTE SENSING OF WATER QUALITY

Research staff have been working with South African scientists to expand the calibration dataset for this method. Dr. Mlotha met with local scientists in January to identify relevant datasets. Additional data may be taken by staff. The target parameters remain water clarity, chlorophyll, and turbidity.

GROUNDWATER-SURFACE WATER INTERACTIONS

Ms. Bakar will begin research on groundwater-surface water interactions with hydrologic models based on data collected from surface water observations and groundwater surveys from electrical resistivity tomography (ERT). Tow preliminary fieldwork sites for this work have been identified: the high-elevation watershed of the western Soutpansburg Mountains, just east of Leshiba Mountain that feeds the Sand River and the Makuleke Wetlands in northern Kruger National Park. The research team has proposed the work in Kruger National Park to South African National Parks (Appendix C). This research constitutes the "under research" phase work listed in the module 1 section of the monitoring and evaluation update in this report.

CITIZEN SCIENCE

The RPI student team has continued to work on the citizen science project for water resources monitoring. This project is inspired by US-based citizen science that uses Google Voice and a server-side python script to collect river height data sent via text message (Fienen and Lowry, 2012). The US project showed that the river level reported by the citizen science program was consistent with traditional data loggers (Lowry and Fienen, 2013). The team is working on enhancing this concept in several ways to make this more applicable to known settings in the Limpopo. Currently, students are working on image processing for a photograph-based system.

REFERENCES

Fienen, M. N., & Lowry, C. S. (2012). Social.Water—A crowdsourcing tool for environmental data acquisition. *Computers & Geosciences*, *49*, 164–169. https://doi.org/10.1016/J.CAGEO.2012.06.015

Lowry, C. S., & Fienen, M. N. (2013). CrowdHydrology: Crowdsourcing Hydrologic Data and Engaging Citizen Scientists. *Ground Water*, *51*(1), 151–156. https://doi.org/10.1111/j.1745-6584.2012.00956.x

MODULE 2: TRAINING, WORKSHOPS, AND CONFERENCES

INTRODUCTION TO REMOTE SENSING

A course on remote sensing analysis was offered at the University of Venda, 20-24 January 2020, taught by WaterQ2 scientist, Dr. Joseph Mlotha.

INTRODUCTION

Water resources provide many essential goods and services to biodiversity and support livelihoods for millions of people. Managing water resources is a critical component for improving food security, conservation of biodiversity, reducing poverty and building health nations for socio-economic development. It is in this context that training was organized as part of capacity building to equip stakeholders and local scientists with some of the needed tools to apply in managing water resources. Remote sensing and Geographical Information systems (GIS) can improve the routine monitoring of water resources especially using some of the physical and biological characteristics to assess water quality and quantity.

PARTICIPANTS

There were 20 participants (Appendix D) drawn from various stakeholders including academia, government and non-governmental organizations (NGOs) with varying backgrounds and at different stages in their career. Amongst the 20 participants, 35% were female and 15% had PhDs. We also had some from Kruger National Park, University of Pretoria and Livhuwani Matsila and Associates.

COURSE DESIGN AND PREPARATION

The course was organized with an aim to empower the participants to apply remote sensing in their research and management of water and natural resources. Participants were requested to bring their own personal laptops for the training, and we used QGIS (Quantum Geographic Information System) open-source software for training. Using an open-source GIS software provides opportunity and assurance to participants that they can continue working on their projects after the training. With the development of open source GIS software, there is hope that the number of researchers and scientists using GIS and remote sensing in water and natural resources management will increase, which can enhance the efficient monitoring of changes in the environment.

Figure 1: Course participants at Univen

SCHEDULE

The daily class schedule was from 8 am to 5 pm with two 30 minutes tea/coffee breaks, one in the morning at 10.30 am and the other in the afternoon at 3.30 pm, and one one-hour lunch break at 12.30 pm. Lunch and tea/coffee breaks were provided by the training sponsors. A class attendance register for participants was signed every day.

COURSE DELIVERY AND FACILITATION

The training approach combined lectures and practical hands-on exercises. In class, we used PowerPoint presentations, questions, and answers, discussions, brainstorming ideas and guided lab exercises. We covered the fundamentals of GIS and remote sensing including the following:

- basics of QGIS -installation, interface, and manipulation,
- sources of data and how to find data,
- image processing and land cover mapping,
- using satellite imagery to estimate water quality,
- applications of remote sensing using QGIS,
- importance and uses of Digital Elevation Model (DEM),
- introduction to Global Position Systems (GPS), and
- project planning and applications using geospatial tools.

Participants were encouraged to discuss and help each other during practical sessions (Figure 2).

Figure 2. Participants discussing a problem during a class.

COMPARING PRE AND POST-TRAINING ASSESSMENT OF THE PARTICIPANTS

A pre-training survey was sent out to all participants before the training started. The survey was prepared with four self-assessment questions which had a ranking scale of 1 (Poor) to 5 (Excellent). The pre-training survey aimed to assess what the participant knew about remote sensing and assessing their capabilities in basic satellite data processing before they go through the training. Another evaluation survey was completed by participants at the end of the training. The post-training evaluations included the four questions modified from the pre-training survey plus twelve other questions which were used to assess the whole training from preparation to implementation. The focus was to evaluate if the training increased participants' understanding and if the knowledge gained could be applied in practice.

The results of the pre-training survey indicate that an average of 52% of the participants were able to identify and use different raster data formats before the training while an average of only 34% were able to acquire and process satellite data. When the participants were asked about their ability to conduct analyses on imagery (e.g. assess land-use or land-use change or calculate NDVI), an average of 40% indicated that they were able and an average of 49% indicated that they were able to display the image analysis outputs as a map or figure (e.g., in a report or other presentation).

Analyzing the results of the post-training evaluations, we see that there is an increase in all the four questions which were asked in a pre-training survey. The increase in the ranges of an average between

26% and 61%. The largest increase is recorded on the ability to process satellite data (data acquisition and image corrections; e.g., Landsat data) versus the ability to apply in practice the knowledge and information gained from participating in the training. Table 1 presents a summary of both pre-training self-assessment surveys and post-training evaluations. The summary results are organized so that we can compare the results of the two assessment surveys using the mean of each question.

TABLE 1: SUMMARY RESULTS OF BOTH PRE-TRAINING SELF-ASSESSMENT SURVEY AND POST TRAINING EVALUATIONS.

QUESTIONS FOR PRE-TRAINING SURVEY	MEAN ON SCALE OF 1 (POOR) TO 5(EXCELLENT), N=20	MEAN ON SCALE OF 1 (POOR) TO 5(EXCELLENT), N=20	QUESTIONS FOR POST TRAINING EVALUATION
		4.58	The objectives of this training were clearly stated and met.
How would you rate your ability to identify and use different raster data formats?	2.60	3.90	Knowledge and information gained from participating: Met my expectations
How would you rate your ability to process satellite data (data acquisition and image corrections; e.g., Landsat data)	1.70	4.75	Knowledge and information gained from participating: Could be applied in practice
How would you rate your ability to conduct analyses on imagery (e.g. assess land-use or land-use change or calculate NDVI)	2.00	4.70	The training has influenced my thoughts on the use of GIS and Remote sensing.
How would you rate your ability to display the image analysis outputs as a map or figure (e.g., in a report or other presentation)	2.45	4.50	The training has increased my knowledge and skills in GIS and Remote sensing.
		4.58	The facilitators were well prepared
		4.55	Physical arrangements: Food service
		4.85	Physical arrangements: Location and its environment
		4.40	What is your overall assessment of the event?
		4.35	Communication before and during the course
		4.35	Course materials/content covered
		3.95	Course objectives or expectations achieved
		4.30	Course presentation and clarity of instructor
		3.95	The software (QGIS) used for the course

TABLE 1: SUMMARY RESULTS OF BOTH PRE-TRAINING SELF-ASSESSMENT SURVEY AND POST TRAINING EVALUATIONS.			
QUESTIONS FOR PRE-TRAINING SURVEY	MEAN ON SCALE OF 1 (POOR) TO 5(EXCELLENT), N=20	MEAN ON SCALE OF 1 (POOR) TO 5(EXCELLENT), N=20	QUESTIONS FOR POST TRAINING EVALUATION
		3.85	Length of the course
		4.45	Overall course organization and presentation
		*100%	Would you be interested in attending a future follow up course on more advanced topics? (1 = Y/ 0 = N)
*this was a Yes/No question and every participant answered, Yes.			

CLOSING OF THE TRAINING

After administering course evaluations to participants, Dr. Joshua Edokpayi a Faculty member at the University of Venda and the collaborator in the WaterQ2 project spoke on behalf of the University of Venda. In his closing remarks, Dr. Edokpayi thanked the organizers of the training for choosing the University of Venda as a venue for the training and reiterated the importance of the training for the participants who are working on different research projects. Participants were reminded to put in practice what they learned and continue using the geospatial tools in solving environmental problems affecting our natural resources. In turn, a representative of the participants spoke expressing gratitude and appreciation for the opportunity to participate in the course. In her remarks, the representative thanked the organizers reiterated how important is the training to their research work and studies. The representative added that the participants are motivated, and they will use the knowledge gained over the training and also, they are interested to have another training.

At the end, the participants were awarded Certificates of completion and a flash disk each with data and study materials to enable them to continue using the newly acquired geospatial tools.

CONCLUSION AND RECOMMENDATION

Despite riot police at the university entrance, the training week was not disturbed by demonstrations or strikes which were being planned by the students in case the negotiations fell apart. Participants were actively involved and showed interest in another training. The data from pre-training and post-training indicate that the training was successful to increase knowledge of the participants. The overall (course organization and presentation) was evaluated at an average of 89%. Despite the success, there are few suggestions that were presented during course evaluation. I have not ranked the suggestions in order of importance, however, most participants indicated that the course duration was short, therefore they suggested to increase the duration to one month.

Other suggestions include the following:

- using ArcGIS instead of QGIS,
- providing water bottles,

- using high-speed computers instead of personal laptops which many of them were low in hard disk space of kept freezing when executing an analysis.
- increase the number of participants to make the training available to more people.
- Include exercises for geological analysis using remote sensing
- Include homework during training
- Include group projects

Specifically on the issue of software, the PIs elected to use QGIS as the platform for geographical information system (GIS) software because (1) it is open source and freely available to all and (2) it is built on an open source platform and readily modifiable in Python, which allows boundless analysis. The use of QGIS does not preclude data from being shared across platforms and functions in a similar fashion to ArcGIS (an ESRI product).

It was unclear to the PIs why some students resisted the use of personal laptops because Univen computer lab terminals were available for all students. The use of personal laptops was a student decision.

PROJECT-SPONSORED EVENTS

WATER INSTITUTE OF SOUTHERN AFRICA (WISA) 2020

Unfortunately, due to Covid-19 complications, this conference has been postponed; it is unclear if the exact schedule at this time.

We planned to publicly announce many of the efforts from this project at this conference, namely, the basin-level report and the Limpopo Resilience Lab. Due to this scheduling change, the partners are reviewing alternatives for these activities. At this time, options include the attendance of a different conference, or the organization or partnership in a virtual event. At this time, another in-person conference poses the same concerns and has the same vulnerabilities as WISA. While a virtual event may be advantageous, we are concerned that internet bandwidth limitations would limit participation from many stakeholders with whom we wish to engage.

ASSOCIATION FOR THE SCIENCES OF LIMNOLOGY AND OCEANOGRAPHY CONFERENCE

This abstract was submitted to the Association for the Sciences of Limnology and Oceanography (ASLO) conference. Unfortunately, due to Covid-19 restrictions, this conference is on hold.

Assessing Patters of Water Quality in Relation to Surface Water Area Variations within the Limpopo River Basin, Southern Africa Using Landsat Imagery (1984-2020)

McArd Joseph Mlotha, David M. Kahler, Joshua N. Edokpayi, and Kevin C. Rose

Changes in the water quantity and quality can have major effects on aquatic ecosystems. While manual sampling can enable characterization through time, it can be cumbersome and time-consuming to accurately map dynamic changes in inland water bodies, especially in developing countries with limited resources. In contrast, geospatial technologies like satellite imagery provide useful tools to monitor water surface area variations together with water quantity and quality over large regions. Here, we explore variation in surface water extent and estimates of water quality characteristics, including

chlorophyll-a, turbidity and water clarity. Additionally, we explore how variation in extent corresponds to variation in water quality seasonally and long-term, 1984-present. We focus on the Limpopo River Basin in southern Africa. The Basin is transboundary, spanning Botswana, Mozambique, South Africa, and Zimbabwe. Much of the Basin is arid, characterized by water scarcity and compounded by a changing climate and increasing drought, as well as increasing withdrawals from agriculture and mining. Our research indicates that using satellite remote sensing applications is effective to monitor the temporal and spatial variations of the surface area and quality of inland water bodies, and that water quantity and quality often co-vary. There is substantial seasonal variation in surface area and water quality, corresponding to precipitation and land-use patterns. At times of peak water stress, water quality is frequently impaired.

MODULE 3: BASIN-LEVEL REPORT

The WaterQ2 team has begun to prepare the draft report on water resources management based on our findings during the first year of the project. Currently, the report is being prepared in parallel with a draft of a manuscript that will be prepared for publication in a peer-reviewed journal. The outline is provided here.

Title: Understanding Strengths, Weaknesses, Opportunities, and Threats to Water Resources Management in the Transboundary Limpopo River Basin

Introduction:

- General overview of the region
    - Transboundary
    - OECD low- and middle-income countries
    - Large basin that has significant correlations to other basins around the world
- Water Resources Law and Policy in Member States
- LIMCOM Treaty and Organization
    - How does effective IWRM occur?
    - Systems thinking to improve planning and consider externalities
- Basin Stressors
    - Population
    - Rapid development
    - Climate change
- Research questions
    - What is the current state of water resources management in the LRB?
    - We can define current state of water resources via:
        - Data: quantity, quality, degree to which data are public, spatial/temporal coverage
        - What are current management strategies?
        - Policies (IWRM)
        - "Best practices"
    - How have management strategies responded to stressors and enhanced resilience?
    - What are the bureaucratic and environmental challenges to improved management as set forth in the IWRM framework, UN transboundary guidance (e.g., 1997 UN Convention on Non-navigational Uses of International Watercourses)?

Background

- Background on IWRM
    - Paris Agreement
    - Economic Advantages
    - UN Definition
    - Limpopo Implementation
- LRB Country Profiles
    - Country Water Policies
        - Domestic
        - Environmental
    - Country IWRM initiatives
- Transboundary Guidance
    - LIMCOM
    - SADC Shared Watercourse
    - UN Guidelines
    - FAO

Methods

- Stakeholder meeting
    - Strengths, weaknesses, opportunities, and threats (SWOT) analysis
- Systematic review of primary and gray (government, NGO, etc) literature
    - Scopus search
        - TITLE-ABS-KEY search
            - (limpopo AND (basin OR catchment OR watershed) AND management) yields 89 articles
            - (limpopo AND (basin OR catchment OR watershed) AND (management OR policy)) yields 95 articles
            - (limpopo AND (river OR basin OR catchment OR watershed) AND (management OR policy)) yields 132
            - Possibly restrict years: 2000-present, 1996-present?
        - Focus Group Surveys- interesting idea to expand on- probably for future papers
        - Gender? - authorship analysis, heads of organizations,
    - Legal case review
        - Polluter pays, legal precedent
    - What data, tools, other resources exist for responding to the needs exposed by the SWOT analysis?
- Spatial analysis
    - Land cover (specific) and NDVI (general) with Landsat
    - Surface water cover, water quality
    - Analysis: 1990 to 2020 in five- or ten-year increments based on wet and dry seasons
    - Land Cover Classes
        - Water
        - Wetland
        - Mining
        - Forest
        - Plantation (based on shape of polygons)

        - Urban
        - Small agriculture (subsistence), (small, fragmented)
        - Commercial agriculture (extensive)
    - Analyses and case studies:
        - Have there been significant changes
        - What correlations exist with land cover or greenness (NDVI)?
        - What correlations exist with water quality?

Results and Discussion

- SWOT results
    - Data
    - Planning for results - long-term planning
    - Polluter pays
        - National Water Act, Part 4, section 19, subsection 5.
        - 2013 Court case
- Systematic review
    - IWRM implementation
    - Data
- Land cover changes
    - Maps and plots to show trends and correlations in land cover and water quality
    - Have there been significant changes in:
        - evergreen forests?
        - agriculture?
        - Have there been trends towards any land cover type?
    - Analyses and case studies:
        - What correlations exist with land cover or greenness (NDVI) and:
            - dam construction?
            - population?
            - types of agriculture?
        - What correlations exist with water quality and:
            - dam construction?
            - population?
            - types of agriculture?
        - How does IWRM implementation of certain systems (dams, treatment facilities, etc) change the local environment in ways that weren't considered?

Conclusions

- Given the state of knowledge, the identified challenges, and the estimated land use, what are the priorities for water management improvement in the LRB?
- Understanding how management of water resources in the Limpopo River Basin adapts to stressors.
- Comparison to transboundary management to nearby basins: Inkomati and Okavango River Basins.

MODULE 4: LIMPOPO RESILIENCE LAB

University of Venda, under the leadership of Dr. Edokpayi, submitted a concept note (application) for additional funding for instruments to the Resilient Waters program last quarter and is still waiting to hear back. The physical space is still being developed because additional resources may be available for the Lab.

MONITORING AND EVALUATION

MODULES 1 AND 3: WATER MONITORING

There are two primary research activities that have continued in this quarter that are supported through this project. They all fall into USAID category, *Production Systems Research*, as they are a component of natural resources management: they are both in the *field-testing* phase of research. The two areas of research are:

- Satellite methods to determine river flow
- Satellite methods to determine water quality (e.g., turbidity and chlorophyll)

The investigators have already begun to prepare a manuscript on the river flow method, which will be submitted to USAID when submitted for publication. For the first quarter, no other activities have reached monitoring values.

TABLE 1: MODULES 1&3 INDICATORS

INDICATOR	DISAGGREGATION	CURRENT VALUE	PROJECT TOTAL
Number of technologies, practices, and approaches under various phases of research, development, and uptake as a result of USG assistance	Phase: Under research	1	3
	Under field testing	2	2
	Made available	0	0
	Demonstrated uptake	0	0
Number of peer-reviewed scientific publications resulting from USG support to research and implementation programs	None	0	0
Number of hectares of land under improved technologies or management practices with USG assistance		0	0
Number of datasets shared, which were generated as a result of USG assistance	Basin country	0	0

Data are being uploaded to Development Data Library (DDL). In September 2019, Dr. David Kahler requested that USAID make the data public. We are still waiting for final approval. No responses have been received from the DDL. This makes it impossible to make progress on the indicator, "number of datasets shared."

MODULE 2. IWRM TRAINING, WORKSHOPS, AND CONFERENCES

Module 2 contains two primary components: convene stakeholder workshops and trainings; and convene future collaborators at conferences. The first stakeholder workshop has been scheduled for August 2019 at CSIR in Pretoria.

The project-level goals for these are to identify environmental champions and cultivate partnerships for future collaborations, especially with the Limpopo Resilience Lab. Project staff has been in close contact with CSIR, Kruger National Park, and Endangered Wildlife Trust. These groups will strengthen the network of water resources and biodiversity professionals in the area.

TABLE 2: MODULE 2 INDICATORS

INDICATOR	DISAGGREGATION	CURRENT VALUE		PROJECT TOTAL	
Number of people trained in sustainable natural resources management and/or biodiversity conservation as a result of USG assistance	Sex	Male	Female	Male	Female
		13	7	18	12
Number of water and sanitation sector institutions strengthened to manage water resources of improve water supply and sanitation services as a result of USG assistance	Institutional scale	0		0	

PROJECT PROGRESS

WORK PLAN PROGRESS

Table 3 outlines progress on work plan activities (outlined in the Mobilization Plan) and the ongoing research activities. As specified in the Project Description, the following activities were planned.

TABLE 3: PROJECT ACTIVITIES

#	ACTIVITY	2019			2020				2021				2021
		2	3	4	1	2	3	4	1	2	3	4	1
	Startup activities: Mobilization Plan, Staffing, EMMP												
1	Establish meteorological, river, and groundwater stations, *Water Monitoring and Algorithm Development* Report		*										
1	Groundwater measurements (ERT), to be included in *Water Monitoring* Report												
1	Develop satellite algorithms												
1	Develop hydrologic and water quality models												
2	Convene stakeholders in workshops												
2	Scientific conferences												
2	Training workshops			*	*								
3	Publish and present basin report												
4	Launch Limpopo Resilience Lab												
			Completed						In-progress/planned				

The activities marked with a star (*) have been adjusted for scheduling purposes. Hydrometeorological data collection was scheduled for July 2019; however, due to scheduling, has been moved to August 2019. This results in a one-month delay of the first report on the locations and data collection outlined in Milestone 4. Additionally, the staff has decided to add training opportunities in January 2020 following

recruitment in the first stakeholder meeting. Groundwater investigations have also been delayed due to an unforeseen shipping delay.

MILESTONE PLAN

TABLE 4: MILESTONE PLAN

#	MILESTONE	2019			2020				2021				2021
	Quarter:	2	3	4	1	2	3	4	1	2	3	4	1
1	Mobilization Plan	Apr											
2	Environmental Mitigation and Monitoring Plan	Jun											
3	Quarterly Report	Jul											
4	Water Monitoring and Algorithm Development Report		Dec*										
5	Stakeholder Workshop Report		Nov										
6	Annual Work Plan		Aug										
7	Quarterly Report		Dec*										
8	Quarterly Report			Apr*									
9	Quarterly Report^				Apr								
10	LRL Website and Planning				Apr								
11	Scientific Conference					Jul							
12	Basin Report					Jul							
13	Quarterly Report					Jul							
14	Stakeholder Workshop Report						Sep						
15	Annual Work Plan						Aug						
16	Quarterly Report						Oct						
17	Quarterly Report							Jan					
18	Quarterly Report^								Apr				
19	Scientific Conference									Jul			
20	Quarterly Report									Jul			

21	Stakeholder Workshop Report	Sep		
22	Water Monitoring: Two manuscripts	Aug		
23	Annual Work Plan	Aug		
24	Quarterly Report	Sep		
25	Quarterly Report		Jan	
26	Basin Report			Mar
27	LRL Continuity Report			Mar
28	Quarterly Report			Apr

Shaded items are completed or pending approval. It is recommended that the Milestone Plan be revised so that the annual cost share report, which was originally marked to occur for the reporting quarters #5, 9, and 12, will be included in quarterly reports, marked with a carrot (^), for reporting quarters #4, 8, and 12. The water monitoring report (Milestone #4) is also marked (*).

FINANCIAL

PRIME RECIPIENT

Duquesne University has used project funds for the expenditures in Table 5. Duquesne University has used other funds for the expenditures in Table 6; these represent cost share.

TABLE 5: PROJECT EXPENDITURES		
ITEM	Q4 EXPENDITURE	PROJECT TOTAL
Sensitive financial information has been withheld from the published report.		
Total	$22,709.48	$238,023.94

Notes: Student support is billed to accounts at the start of the University's fiscal year in June for the upcoming academic year.

TABLE 6: COST SHARE		
ITEM	Q4 EXPENDITURE	PROJECT TOTAL
Sensitive financial information has been withheld from the published report.		
Total	$0	$52,049.46

RENSSELAER POLYTECHNIC INSTITUTE (RPI)

TABLE 6: COST SHARE		
ITEM	PY 2019-20	PROJECT TOTAL
Sensitive financial information has been withheld from the published report.		
Total	$27,121.13	$27,121.13

University of Venda does not have any cost share to report this project year.

APPROVAL

This Quarterly Report has been received and approved by USAID. This satisfies the requirements set forth in the Milestone Plan, item #9: Completion of Quarterly Report (Q4).

Signature: _____

Name: _____
Agreement Officer's Representative

Date: _____

APPENDIX A: GRADUTE RESEARCH ASSISTANT (GRA)

The resume for Sophia Bakar is included here.

Personal information was withheld from the published version of this report.

APPENDIX B: PROJECT WEBSITE TRAFFIC

Site visits have come from around the world (Figure B1) with a concentration from the United States of America and South Africa (Table B1).

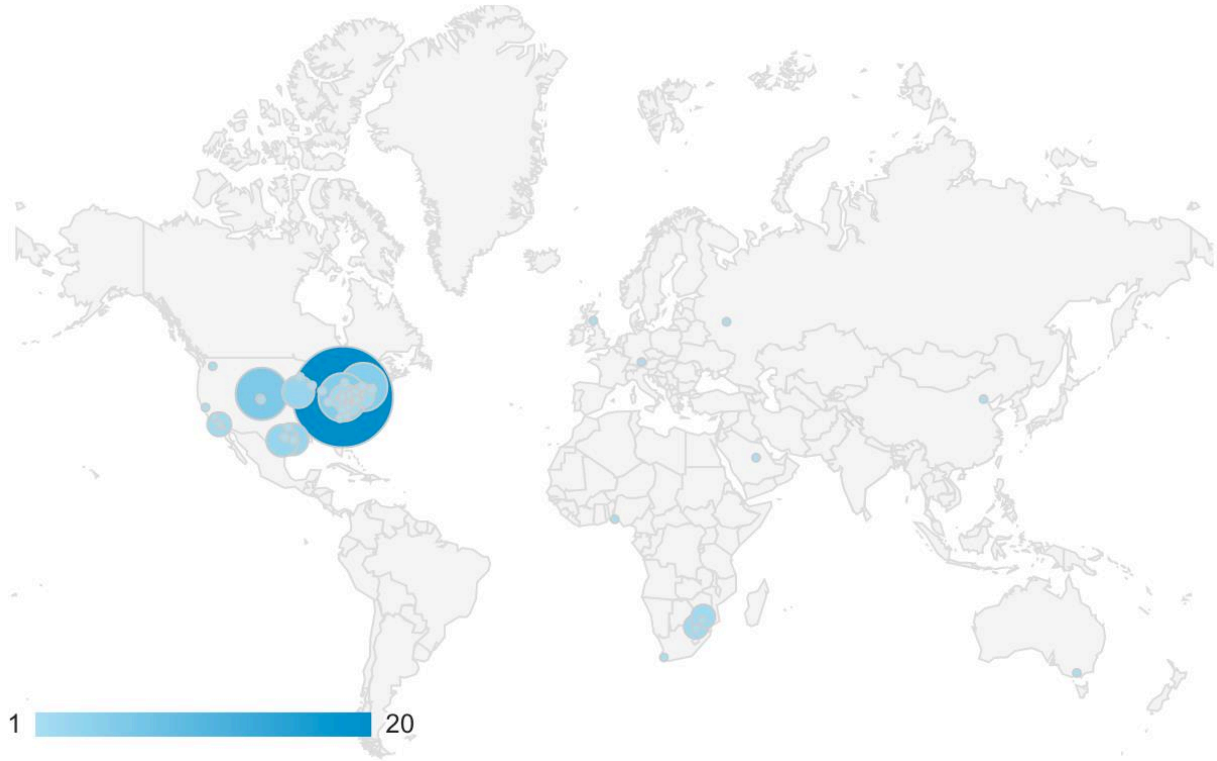

Figure B1: Map of audience for 01 January to 31 March 2020. Plotted are unique users for the period according to access of any page within the Limpopo Resilience Lab website (as indicated in Appendix A, excludes the DSC). Graphic from Google Analytics.

TABLE B1: GEOGRAPHICAL WEBSITE TRAFFIC REPORT FROM 01 JUNE TO 10 DECEMBER 2019

COUNTRY	UNIQUE USERS	SESSIONS	PAGES PER SESSION	AVERAGE SESSION DURATION (H:MM:SS)
United States of America	99	120	1.60	0:00:28
South Africa	6	9	1.67	0:00:14
Australia	1	1	6	0:00:00
Canada	1	1	3	0:00:00
China	1	1	1.5	0:00:00
Germany	1	1	5	0:00:00
United Kingdom	6	1	1	0:00:00
Nigeria	2	1	1	0:00:00

Russia	1	1	1	0:00:00
Saudi Arabia	1	1	1	0:00:00
Unknown	1	1	1	0:00:00

There has been a decrease in site visits from the previous report. This is expected as we do not have any training offered at this time.

APPENDIX C: KRUGER NATIONAL PARK APPLICATION

Some personal information has been removed.

South African
NATIONAL PARKS

RESEARCH PROJECT APPLICATION FORM

1. TITLE OF THE PROJECT

Electrical resistivity tomography (ERT) investigation of water resources in the Luvuvhu/Limpopo confluence and Makuleke Wetland

2. CONTACT DETAILS

2.1 SENIOR RESEARCHER CONTACT DETAILS

- S. A. Bakar
  Graduate Research Assistant (thesis research)
  Duquesne University
  Pittsburgh, PA 15282, USA
  bakars@duq.edu

2.2 CO-WORKERS CONTACT DETAILS

- Dr. D. M. Kahler
  Assistant Professor (thesis committee chair)
  Duquesne University
  600 Forbes Ave.
  Pittsburgh, PA 15282, USA
  +1 (202) 630-8757
  kahlerd@duq.edu, david.m.kahler@gmail.com
- Dr. J. N. Edokpayi
  Senior Lecturer
  University of Venda
  Private Bag x5050

Thohoyandou 0950, South Africa
Joshua.Edokpay@univen.ac.za
School of Environmental Sciences, University of Venda

- Dr. K. C. Rose
  Assistant Professor
  Rensselaer Polytechnic Institute
  110 Eight St.
  Troy, NY 12180, USA
  rosek4@rpi.edu
- Dr. E. Riddell
  Water Resources Manager, Conservation Services
  Kruger National Park
- R. Petersen
  Freshwater Scientist, Scientific Services
  Kruger National Park
- M. L. Martin
  Graduate Research Assistant
  Duquesne University
  Pittsburgh, PA 15282, USA
  martinm4@duq.edu
- Thivhonali Hilton
  Graduate Research Assistant
  University of Venda
  Thohoyandou 0950
  Limpopo, South Africa
- Ntwanano Mutileni
  Graduate Research Assistant
  University of Venda
  Thohoyandou 0950
  Limpopo, South Africa

3. PARK (S) IN WHICH THE STUDY WILL BE CONDUCTED

Kruger National Park, Makuleke Wetland Contractual Park

4. IN A FEW WORDS, PLEASE EXPLAIN WHY THIS WORK NEEDS TO TAKE PLACE WITHIN A NATIONAL PARK

This proposed research will leverage existing research efforts and funding to understand water resources and biodiversity in the Limpopo River Basin. Kruger National Park is an important area in this transboundary watershed. Specifically, several rivers that drain high-elevation catchments come together in the Makuleke wetlands just before flowing into Mozambique and the Olifants River, which is affected by mining operations in South Africa flows through Kruger National Park as it passes to Mozambique. Complementing our existing research in the Limpopo River Basin, our proposed research in Kruger National Park focuses on water quantity and quality across the Park, including areas that are not necessarily in the Limpopo River Basin.

The proposed work supports our collaborative research program, Understanding Regulators of Kruger Park Water Quantity and Quality to Better Conserve Biodiversity (Kahler, 2020). The primary goal of this project is to determine the overall flow from the Luvuvhu catchment to the total Limpopo water resources. Specifically, we hypothesize that there is a significant contribution of groundwater flow through the Makuleke region. This would further support our hypothesis that the high-elevation catchments play an important role in water resources. This project will, through ERT survey contribute to the baseline conceptual model development of groundwater-surface water process, which to our knowledge, has not yet been undertaken in the Makuleke wetlands.

Kruger National Park is an important and unique area as it is home to emblematic and critical species. The groundwater-surface water interactions play a role in the water available to these macrofauna. We expect that our examination of groundwater flow in the Makuleke will elucidate the water availability.

5. KEYWORDS

Water Resources Management; Water Quality; Water Quantity; Groundwater; Biodiversity

6. EXECUTIVE SUMMARY

6.1 RATIONALE

The transboundary Limpopo River Basin crosses Botswana, Zimbabwe, South Africa, and Mozambique. At over 400,000 km2, the Limpopo Basin is home to 18 million people living in both rural and urban areas. Industries in the Basin include businesses in the urban areas and water-intensive uses such as agriculture and mining; industrial water use is growing rapidly (Petrie et al., 2014). In addition to the human residents, the Basin contains some of the most biodiverse natural areas on the planet (Kahinda et al., 2016).

The rainfall in the Basin is heterogeneous with some sub-basins receiving less than 400 mm on average and other downstream sub-basins in Mozambique receiving over 750 mm annually; meteorological stations located in close proximity demonstrate substantial spatial variation within sub-basins (Petrie et al., 2014). The Basin has experienced severe droughts in the last decade. In addition to the variation in the amount of rainfall, the timing, especially the start of the growing season, has varied significantly (Edokpayi et al., 2018).

Investigation in Kruger National Park will help us understand the greater water resources in the transboundary Limpopo River Basin and the role of water resources management for ecosystem services including biodiversity conservation, domestic, agricultural, and industrial uses.

This research focuses on the use of specialized measurement techniques for groundwater and traditional surface water monitoring; these data will be used in hydrologic models to enhance our overall understanding of the hydrology in the area and improve basin-wide water management. The investigation in the Makuleke wetlands and surrounding areas provide a protected natural setting where groundwater and surface water interact in unique ways (Figure C1). The 22,000 ha Makuleke area (Fabricius & Collins, 2007) is known for the community that inhabits it and the waterbodies that comprise the Makwadzi Pan, which has shown variations in paleoclimate (Ekblom et al., 2012).

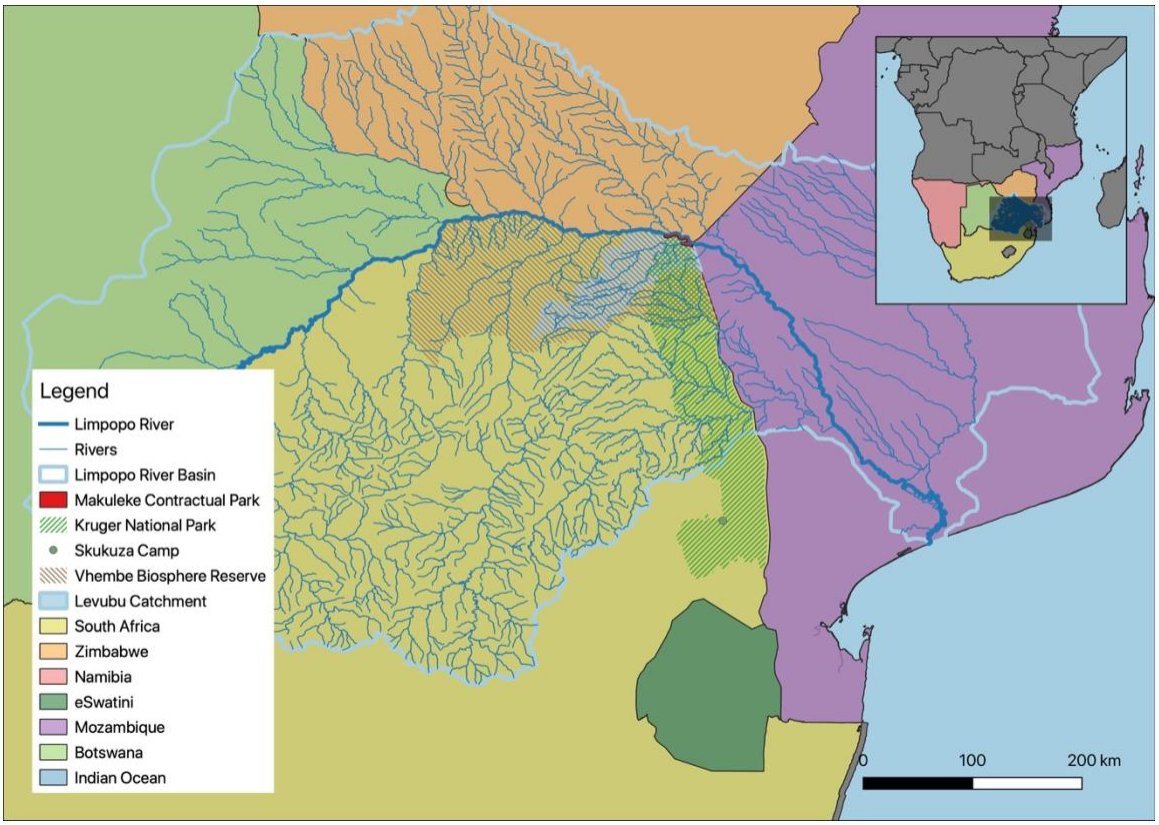

Figure C1: Location of the Makuleke Contractual Park within Kruger National Park in South Africa.

6.2 METHODS

We plan to use electrical resistivity tomography (ERT) to resolve the shape of the water table over time (Hubbard et al., 1999) and estimate the parameters for groundwater flow (Vanderborght et al., 2005). We will use induced polarization (IP) to further estimate the aquifer parameters (Slater, 2007), specifically porosity and permeability. Measurements will be taken along multiple transects throughout the area both parallel and perpendicular to the land surface gradient as a surrogate for the aquifer (Figure C2). Measurements will also be made near perennial and annual surface water bodies.

We plan to configure the instrument to sample electrical resistivity based on a Wenner array and a Schlumberger array; based on our experience, we expect that our linear 48 electrode, 240 m array will sense approximately 80 m in depth. Water has a significantly higher conductivity than the air-water mixture present in the vadose (unsaturated) zone; this allows the instrument to sense an abrupt decrease in resistivity at the piezometric surface (water table). The depth of the water table will indicate the amount of aquifer water storage and the gradient of the water table, with other parameters, will indicate the transport of water through the aquifer. These measurements over time will allow us to monitor the groundwater component of the local water balance.

In the saturated aquifer, solid particles, which have an intrinsic charge, have bound layer (called the Stern layer) and a diffuse layer of ions in the water that surround the solid particle called an electrical double layer (EDL). This layer is subject to polarization during the imposed signal from the instrument (Figure 3), which is called induced polarization (IP). When the emitted signal is turned off, the receiver

continues to monitor for changes and detects the relaxation of the EDL. The signal, measured as resistivity, is related to the permeability of the soil (Dahlin et al., 2002) in that thin EDL due to smaller individual water channels are more similar to clay (Leroy & Revil, 2009) compared to larger individual water channels, which are more similar to sandy deposits (Revil, 2012).

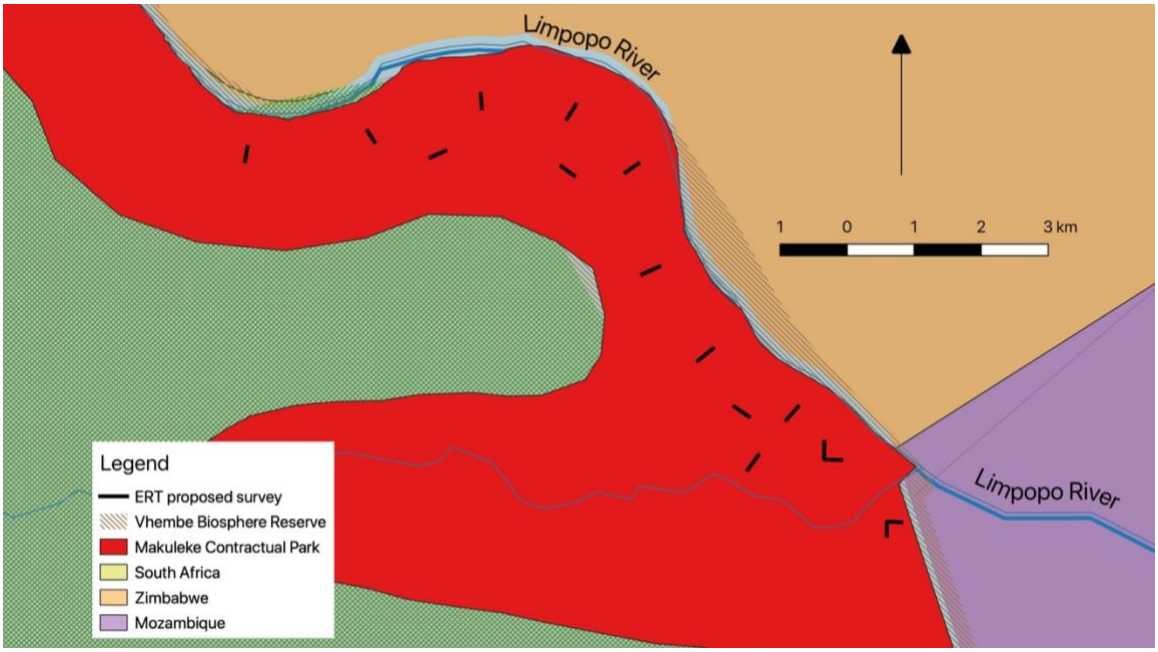

Figure 2: Proposed ERT survey locations surrounding the Luvuvhu-Limpopo confluence. These survey transects were selected by examination of satellite images and may be adjusted based on the hydraulic measurements and consultation with Park scientific staff and other stakeholders to minimize disturbances to environmentally or culturally sensitive areas.

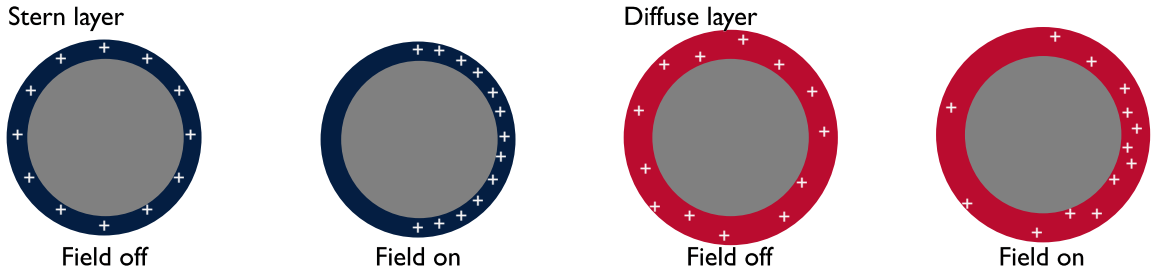

Figure 3: EDL from charged dielectric material, from (adapted from Pesch, 2019). Both the fixed (a) and diffuse (b) layers are diagramed. IP measures the response from the polarized (right of each layer) to return to a normal distributed layer.

Darcy's Law (Freeze & Cherry, 1979) relates the specific discharge of an aquifer to the hydraulic conductivity and the pressure gradient, typically taken as the slope of the piezometric surface.

We will use ERT data collected from this project to construct hydrologic models of groundwater-surface water interactions in MODFLOW (U.S. Geological Survey) (Brunner et al., 2010; Guevara Ochoa et al., 2020). Additionally, for basin-scale monitoring, we will use the U.S. Army Corps of Engineers, Hydrologic Engineering Center software suite: Hydrologic Modeling System (HEC-HMS) and River Analysis System (HEC-RAS). Specifically, HEC-HMS will be used to estimate the general baseflow contributions based on the flow and precipitation data available in the area. These models will be used to determine the groundwater flow into the Limpopo River. We will also consider observations made

by satellite gravity anomaly from the Gravity Recovery and Climate Experiment (GRACE) data (Richey et al., 2015).

6.3 OBJECTIVES

Our objective in this project is to collect water table height and gradient, and induced polarity data that can be used in hydrologic models. These data and models will be used to measure the groundwater resources, volume and flow, and help elucidate the groundwater-surface water interactions in the Makuleke area. Multiple samples taken across seasons through multiple years will help to determine the role of the groundwater flow in the Levuvhu catchment.

This supports the goals of our overall program through the estimation of the groundwater flow into the Limpopo River and elucidate the groundwater-surface water interactions in the Makuleke wetlands and surrounding water bodies. We hope that this will support the conservation work by Kruger with increased groundwater monitoring.

Groundwater in southern Africa is an important resource especially in the context of climate change. Groundwater in the Limpopo Basin holds great potential for increased water access; however, groundwater measurement data are currently insufficient to calculate sustainable total withdrawal rates (Petrie et al., 2014).

Our objective is that resource managers will have an improved basis for scientifically based decisions and may be able to utilize groundwater resources more effectively to increase (e.g., agricultural) productivity and conserve biodiversity with improved data collection, validation, and sharing of these data.

6.4 OUTCOMES AND MANAGEMENT IMPLICATIONS

Our goals are to support Basin stakeholders, including Kruger National Park, to improve governance around water resources management and water security in the Basin. We hope to accomplish this by collecting and sharing hydrologic data, training students, resource managers, and decision-makers, facilitating networking and communication among institutions, and establishing and supporting dedicated technical resources in the Limpopo Resilience Lab housed at the University of Venda.

In Kruger, we will expand our data collection on water quality and quantity. Our focus will be in the Makuleke Wetlands, a unique hydrological system. Our current work includes the hydrodynamics and water quality of the Luvuvhu/Mutale system. The Luvuvhu River joins the Limpopo River in Kruger with the Makuleke Wetlands at their confluence. Data collection will greatly assist the modeling of water quality and quantity in these northern watersheds. We also seek collaborations with Kruger staff for other mutually beneficial work throughout the Park.

6.5 SIGNIFICANT RISKS

We have examined the potential impact of the use of Electrical Resistivity Tomography (ERT) in our existing Environmental Mitigation and Monitoring Plan (EMMP) (https://pdf.usaid.gov/pdf_docs/PA00TRM9.pdf). The instrument involves hammering 48 metal electrodes (steel, 1 cm diameter, 5 cm into the soil). To mitigate potential impacts, we will not insert electrodes into steep slopes or sensitive soils or delicate vegetation.

6.6 RESOURCES

This project will involve fieldwork in the Makuleke wetland area. We request scientist lodging at the Pafuri Teba camp. To collect data with the ERT and geographic surveys, we request one game guard each day of fieldwork; we estimate a set of surveys will take approximately five days to complete. We will conduct a set of surveys twice each year for two years, currently scheduled to start August 2020 and end March 2022. Field teams typically include three or four scientists.

7. LITERATURE REVIEW

Understanding water quantity and quality is a key global research challenge (Carpenter et al., 2011). Both groundwater and surface freshwater play a critical role in supporting public health, food security, global carbon cycling, and biodiversity (e.g., Dodds et al., 2009; Fleming et al., 2002; O'Reilly et al., 2015; Tranvik et al., 2009). Freshwater losses have the potential to threaten both human societies as well as the biodiversity that supports ecosystem services (Cardinale et al., 2012). Proper management depends on understanding the ecology of aquatic ecosystems as well as the hydrology of both surface and groundwater systems.

Of particular interest for this project is the seasonal variations in baseflow (Chow et al., 1988). The alteration of baseflow is primarily responsible for the establishment of annual ponds (Sophocleous, 2002), which can play an important role in water resources for animals and play a unique role in biogeochemical cycles (Brunke & Gonser, 1997).

The challenges of climate change are not felt equally around the world, both in terms of human impacts as well as ecosystems. For example, southern Africa, including the country of South Africa, is a dry region in a monsoonal climate. The region is getting drier and hotter. The region also contains a disproportionate concentration of Earth's biodiversity and many low-income populations. Changing precipitation timing and reduced volume threatens the quality and very existence of aquatic ecosystems, including constructed reservoirs, wetlands, and river networks. In turn, these climate changes threaten regional biodiversity as well as the economic activities that depend on water.

8. RATIONALE AND BACKGROUND

8.1 WHAT IS THE CONSERVATION, RESEARCH OR MANAGEMENT PROBLEM?

The rivers of Kruger National Park contain nearly 50 fish species, yet little is known about how these fishes respond to environmental perturbations, including climate change impacts. For example, the thermal tolerances of fishes are largely unknown. Air temperature have been increasing with unknown consequences. Additionally, Kruger, together with water resource management agencies and partners, maintain specific environmental flows in Park's rivers through coordinated restrictions and operating rules for upstream dams to release water during the dry season when flows fall below a legally defined minimum. However, dam releases are usually pulsed water from the hypolimnion of the water column and the temperature of released water may be substantially colder than what is in the rivers beforehand. The ecological consequences of pulsed dam releases are unknown; while they may preserve minimum environmental flows, the cold water may have other adverse ecological impacts. Additionally, anecdotal evidence indicates that deep river pools are filling in and turbidity levels are increasing with time, further

stressing aquatic biodiversity. Furthermore, we seek opportunities to engage in collaborations with other scientists.

8.2 WHY IS IT IMPORTANT?

Characterizing seasonal and long-term trends and patterns in water quality characteristics such as water temperature, turbidity, dissolved oxygen, and conductivity provide a first step toward characterizing the impacts of upstream environmental and climate changes on aquatic biodiversity.

9. OBJECTIVES & KEY QUESTIONS

The goal of the project is to develop groundwater-surface water interactions in the Makuleke Wetlands area. In order to do this, we will use ERT with IP to characterize the aquifer and monitor flow in wetlands and area around the confluence of the Levuvhu and Limpopo Rivers.

10. WORK PROCEDURES

10.1 STUDY AREA

The Makuleke Wetlands area and pans along with the Levuhvu River confluence.

10.2 TYPE OF ACTIVITIES

10.2.1 study subjects and material to be collected

Only water samples will be collected to measure water quality parameters. In addition to collected water samples, we may deploy internally powered and internally-logging sensors measuring water quality variables such as temperature, pressure (to determine depth), and turbidity, and electrical conductivity. The specific sites we would deploy these sensors would be made in consultation of Park scientists and include fixed points close to or within KNP, namely Mhinga A9H012, Mutale A9H013 and Parfuri Bridge A9H032 at a minimum. All data from sensors will be made publicly available to the degree possible (assuming approval from Kruger NP scientists) following downloading and quality checks.

10.2.2 frequency of collection

ERT survey sets will be conducted in the dry season (August) and the wet season (March).

10.2.3 sample size and amount

ERT transects just under 300 m.

10.2.4 where will voucher specimens will be housed

No specimens will be taken.

10.2.5 capture (physical or chemical) or restraint description

No specimens will be taken.

10.2.6 drugs, dosage and administration methods

These are not included in this research program.

10.2.7 biological material to be collected and method of collection

No biological material will be collected in this project.

11. BIOLOGICAL SAMPLES REQUESTED (COMPLETE THIS SECTION ONLY IF YOUR RESEARCH REQUESTS ALREADY SAMPLES)

No biological samples will be collected.

12. ETHICAL CLEARANCE (IF APPLICABLE)

Not applicable.

13. STRATEGIC, SUPPORT AND LOGISTICS

13.1 FOR WHOM IS THE PROGRAM BEING UNDERTAKEN?

The planned research will be undertaken for the benefit of the Park, Park scientists, and academic partners. Results will be published in open access data repositories and peer-reviewed journals.

13.2 DURATION OF THE PROJECT?

Our plan was to conduct extensive fieldwork in August 2020. Due to Covid-19 restrictions, this fieldwork will be significantly delayed. To collect data for the models, we request three years for data collection, which will bring us to August 2023.

13.3 WHO WILL BENEFIT FROM THE PROJECT BEING ACHIEVED?

Broad benefits include to Park scientists, Park visitors, and the scientific community; this will support our ongoing research in the Limpopo River Basin.

13.4 WHAT QUALIFICATION IF ANY WILL BE OBTAINED FROM THE STUDY?

We expect the data collected to substantially contribute to a Master of Science degree awarded by Duquesne University.

13.5 WHO IS THE FUNDING PROVIDER AND WHAT IS THE ESTIMATED COST OF THE PROJECT?

All equipment will be provided by US based collaborators Kahler and Rose through research grants. Specific support will be detailed in project proposals.

Currently supported by: United States Agency for International Development
Southern Africa Regional Mission
Fixed Amount Award 72067419FA00001
March 2019 – March 2022

13.6 HOW WILL THE STUDY BENEFIT THE NATIONAL PARK'S MANAGEMENT OBJECTIVES?

Data collected will help in understanding the factors regulating Park biodiversity.

13.7 WHAT ASSISTANCE IS EXPECTED FROM SANPARKS?

We plan for each survey to last five days for four researchers; therefore, 28 person-nights accommodations and 5 days of game guards. We plan for two surveys a year, one in the dry season (around July and August) and one in the wet season (around December and January).

14. MAJOR MILESTONES

Surveys are planned to occur in August 2020 and March 2021. Each field survey will consist of:

Day 1 Arrival and equipment setup

Day 2 Geographic survey of the area, water depths of pans, other water bodies

Day 3-6 ERT transects

Day 7 Departure day, cleanup camp, pack instruments

15. RISKS

Consider risk to self as well as to risk of not completing the study

Project Risks: The proposed project has few risks. The largest may be of in situ equipment breaking free and washing downstream. However, sensors are small and will be well-anchored, so this is likely a small risk.

Environmental Impact: No impacts are predicted; we have monitoring procedures in place to ensure environmental protection.

REFERENCES

Brunke, M., & Gonser, T. (1997). The ecological significance of exchange processes between rivers and groundwater. *Freshwater Biology*, *37*(1), 1–33. https://doi.org/10.1046/j.1365-2427.1997.00143.x

Brunner, P., Simmons, C. T., Cook, P. G., & Therrien, R. (2010). Modeling Surface Water-Groundwater Interaction with MODFLOW: Some Considerations. *Groundwater*, *48*(2), 174–180. https://doi.org/10.1111/j.1745-6584.2009.00644.x

Cardinale, B. J., Duffy, J. E., Gonzalez, A., Hooper, D. U., Perrings, C., Venail, P., … Naeem, S. (2012). Biodiversity loss and its impact on humanity. *Nature*, *486*, 59. https://doi.org/https://doi.org/10.1038/nature11148

Carpenter, S. R., Stanley, E. H., & Vander Zanden, M. J. (2011). State of the World's Freshwater Ecosystems: Physical, Chemical, and Biological Changes. *Annual Review of Environment and Resources*, *36*(1), 75–99. https://doi.org/10.1146/annurev-environ-021810-094524

Chow, V. Te, Maidment, D. R., & Mays, L. W. (1988). *Applied Hydrology*. New York: McGraw-Hill.

Dahlin, T., Leroux, V., & Nissen, J. (2002). Measuring techniques in induced polarisation imaging. *Journal of Applied Geophysics*, *50*(3), 279–298. https://doi.org/https://doi.org/10.1016/S0926-9851(02)00148-9

Dodds, W. K., Bouska, W. W., Eitzmann, J. L., Pilger, T. J., Pitts, K. L., Riley, A. J., … Thornbrugh, D. J. (2009). Eutrophication of U.S. Freshwaters: Analysis of Potential Economic Damages. *Environmental Science & Technology*, *43*(1), 12–19. https://doi.org/10.1021/es801217q

Edokpayi, J. N., Rogawski, E. T., Kahler, D. M., Hill, C. L., Reynolds, C. F., Nyathi, E., … Dillingham, R. A. (2018). Challenges to Sustainable Safe Drinking Water: A Case Study of Water Quality and Use across Seasons in Rural Communities in Limpopo Province, South Africa. *Water*, *10*(2), 159. https://doi.org/10.3390/w10020159

Ekblom, A., Gillson, L., Risberg, J., Holmgren, K., & Chidoub, Z. (2012). Rainfall variability and vegetation dynamics of the lower Limpopo Valley, Southern Africa, 500AD to present. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *363–364*, 69–78. https://doi.org/https://doi.org/10.1016/j.palaeo.2012.08.015

Fabricius, C., & Collins, S. (2007). Community-based natural resource management: governing the commons. *Water Policy*, *9*(S2), 83–97. https://doi.org/10.2166/wp.2007.132

Fleming, L. E., Rivero, C., Burns, J., Williams, C., Bean, J. A., Shea, K. A., & Stinn, J. (2002). Blue green algal (cyanobacterial) toxins, surface drinking water, and liver cancer in Florida. *Harmful Algae*, *1*(2), 157–168. https://doi.org/https://doi.org/10.1016/S1568-9883(02)00026-4

Freeze, R. A., & Cherry, J. A. (1979). *Groundwater*. Englewood Cliffs, NJ: Prentice Hall.

Guevara Ochoa, C., Medina Sierra, A., Vives, L., Zimmermann, E., & Bailey, R. (2020). Spatio-temporal patterns of the interaction between groundwater and surface water in plains. *Hydrological Processes*, *34*(6), 1371–1392. https://doi.org/10.1002/hyp.13615

Hubbard, S. S., Rubin, Y., & Majer, E. (1999). Spatial correlation structure estimation using geophysical and hydrogeological data. *Water Resources Research*, *35*(6), 1809–1825. https://doi.org/10.1029/1999WR900040

Kahinda, J. M., Meissner, R., & Engelbrecht, F. A. (2016). Implementing Integrated Catchment Management in the upper Limpopo River basin: A situational assessment. *Physics and Chemistry of the Earth, Parts A/B/C*, *93*, 104–118. https://doi.org/https://doi.org/10.1016/j.pce.2015.10.003

Leroy, P., & Revil, A. (2009). A mechanistic model for the spectral induced polarization of clay materials. *Journal of Geophysical Research: Solid Earth*, *114*(B10). https://doi.org/10.1029/2008JB006114

O'Reilly, C. M., Sharma, S., Gray, D. K., Hampton, S. E., Read, J. S., Rowley, R. J., … Zhang, G. (2015). Rapid and highly variable warming of lake surface waters around the globe. *Geophysical Research Letters*, *42*(24), 10,710-773,781. https://doi.org/10.1002/2015GL066235

Pesch, G. (2019, January 31). *On the dielectrophoretic particle retention in porous media*.

Petrie, B., Chapman, A., Midgley, A., & Parker, R. (2014). *Risk, Vulnerability, and Resilience in the Limpopo River Basin: Climte change, water, and biodiversity - a synthesis*. Cape Town, South Africa.

Revil, A. (2012). Spectral induced polarization of shaly sands: Influence of the electrical double layer. *Water Resources Research*, *48*(2). https://doi.org/10.1029/2011WR011260

Richey, A. S., Thomas, B. F., Lo, M.-H., Reager, J. T., Famiglietti, J. S., Voss, K., … Rodell, M. (2015). Quantifying renewable groundwater stress with GRACE. *Water Resources Research*, *51*(7), 5217–5238. https://doi.org/10.1002/2015WR017349

Slater, L. (2007). Near Surface Electrical Characterization of Hydraulic Conductivity: From Petrophysical Properties to Aquifer Geometries—A Review. *Surveys in Geophysics*, *28*(2), 169–197. https://doi.org/10.1007/s10712-007-9022-y

Sophocleous, M. (2002). Interactions between groundwater and surface water: the state of the science. *Hydrogeology Journal*, *10*(1), 52–67. https://doi.org/10.1007/s10040-001-0170-8

Tranvik, L. J., Downing, J. A., Cotner, J. B., Loiselle, S. A., Striegl, R. G., Ballatore, T. J., … Weyhenmeyer, G. A. (2009). Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology and Oceanography*, *54*(6part2), 2298–2314. https://doi.org/10.4319/lo.2009.54.6_part_2.2298

Vanderborght, J., Kemna, A., Hardelauf, H., & Vereecken, H. (2005). Potential of electrical resistivity tomography to infer aquifer transport characteristics from tracer studies: A synthetic case study. *Water Resources Research*, *41*(6). https://doi.org/10.1029/2004WR003774

APPENDIX D: PARTICIPANT LIST

TABLE D1: PARTICIPANTS IN INTRODUCTION TO REMOTE SENSING			
FIRST NAME	LAST NAME	INSTITUTIONAL AFFILIATION	EMAIL
Participant personally identifiable information has been removed from the public version of this report.			

WaterQ2: Understanding Water Quality and Quantity in the Limpopo Basin