DETERMINATION OF WATER RESOURCE CLASSES, RESERVE AND RESOURCE QUALITY OBJECTIVES STUDY FOR SECONDARY CATCHMENTS A5 – A9 WITHIN THE LIMPOPO WATER MANAGEMENT AREA (WMA 1) AND SECONDARY CATCHMENT B9 IN THE OLIFANTS WATER MANAGEMENT AREA (WMA 2)

WETLAND ASSESSMENT VOLUME 2

ECOLOGICAL WATER REQUIREMENTS OF THE NYLSVLEY AND MAKULEKE FLOODPLAIN WETLANDS

FINAL DRAFT

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Cover page photo credit: View of the Luvuvhu River, Makuleke area. Photo from Lee Berger's Lanner Gorge expedition. 29 July 2007. Author Profberger at English Wikipedia

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Report Title:	Wetland Assessment Volume 2 – EWR of Nylsvley and Makuleke Floodplain Wetlands
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Director

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Date

DOCUMENT INDEX

Reports that will be produced as part of this project are indicated below.

The bold type indicates this report.

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01	WEM/WMA01&02/00/CON/RDM/0122	Inception Report
02	WEM/WMA01&02/00/CON/RDM/0222	Water Resources Information Gap Analysis Report
03	WEM/WMA01&02/00/CON/RDM/0322	Delineation and Status Quo Report
04	WEM/WMA01&02/00/CON/RDM/0422	Linking the value and condition of the Water Resources Report
05	WEM/WMA01&02/00/CON/RDM/0522	Site Selection and verification EWR Report
06a	WEM/WMA01&02/00/CON/RDM/0123a	River Assessment (Volume 1) – EcoCategorisation Report
06b	WEM/WMA01&02/00/CON/RDM/0123b	River Assessment. (Volume 2) – Ecological Water Requirements Report
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ACRONYMS	DESCRIPTION
AIP	Alien Invasive Plant
CRS	Coordinate Reference System
DRIFT	Downstream Response to Imposed Flows Transformation
DSS	Decision Support System
DTM	Digital Terrain Model
DWS	Department of Water and Sanitation
EFlows	Environmental Flows
EI	Ecological Importance
ES	Ecological Sensitivity
EWR	Ecological Water Requirement
IBA	Important Birding Area
IHI	Index of Habitat Integrity
KNP	Kruger National Park
LIMCOM	Limpopo Watercourse Commission
MS	Microsoft
NLC	National Land Cover
PES	Present Ecological Status
RDM	Resource Directed Measures
REC	Recommended Ecological Category
RQO	Resource Quality Objectives
SC	Secondary Catchments
SoW	Scape of Work
TEC	Target Ecological Category
ToR	Terms of Reference
WMA	Water Management Area
WQ	Water Quality

UNIT	DESCRIPTION
%	percentage
km	kilometer
km^2	kilometer squared
m	meter
m/s	meters per second
m^3/s	meters cubed per second
$m^3 \times 10^6$	Million cubic meters
N/m^2	Newtons per square meter
Q	Discharge

EXECUTIVE SUMMARY

The overall objective of the study is to classify and determine the Reserve and Resource Quality Objectives (RQOs) for all significant water resources in Secondary Catchments (SCs) A5-A9 in the Limpopo Water Management Area (WMA) and SC B9 in the Olifants WMA.

The Scope of Work (SoW) as stipulated in the Terms of Reference calls for:

- Coordinate the implementation of the Water Resources Classification System (WRCS), as required in Regulation 810 in Government Gazette 33541, by classifying all significant water resources in the Limpopo WMA (secondary catchments A5-A9) and Olifants WMA (secondary catchment B9).
- Determine the water quantity and quality components of the groundwater and surface water (rivers and wetlands) Reserve.
- Determine Resource Quality Objectives (RQOs) using the Department of Water and Sanitation Procedures to Determine and Implement Resource Quality Objectives.

The study area encompasses the Limpopo WMA SC A5 – A9 and the Olifants WMA SC B9 (**Figure E1**). The area spans six river catchments: Lephalala, Mogalakwena, Sand, Nzhelele and Luvuvhu rivers in the Limpopo WMA and the Shingwedzi river in the Olifants WMA. There are two RAMSAR sites in the study area, Nylsvley and the Makuleke wetland complex (**Figure E1**) which are the focus of this report.

There are no formal RDM methods that are appropriate for use for the Nyl and Luvuvhu River floodplains. Furthermore, investigations of the EWR for the two areas require a reliable and efficient hydrodynamic model. For this reason, the approach adopted for the EWR assessments was to:

- focus on developing a reliable and efficient hydrodynamic model to predict the extent and duration of flooding on the floodplains.
- create vegetation maps and groundtruth the mapped plant communities.
- review the literature on key biota and undertake an EcoStatus assessment based on existing information.
- populate a DRIFT model for each floodplain that represents a sound understanding of the hydro-ecological functioning.
- evaluate the ecological outcome of future development or climate change scenarios as appropriate.

As part of developing wetland-scale hydrodynamic models, it is necessary to link depth of inundation to the underlying landcover and distribution of vegetation types, which requires mapping or classification. The vegetation of both floodplains was assessed on two separate field trips and the data were classified into vegetation types, lifeforms and dominant species. These vegetation types were then compared with, and matched to, land cover classes that were classified and mapped remotely from aerial imagery portraying a range of spectral bands from satellite data, mostly Sentinel 2.

The vegetation maps of the Nyl River and Luvuvhu River floodplains are shown in **Figure E2** and **Figure E3** respectively.

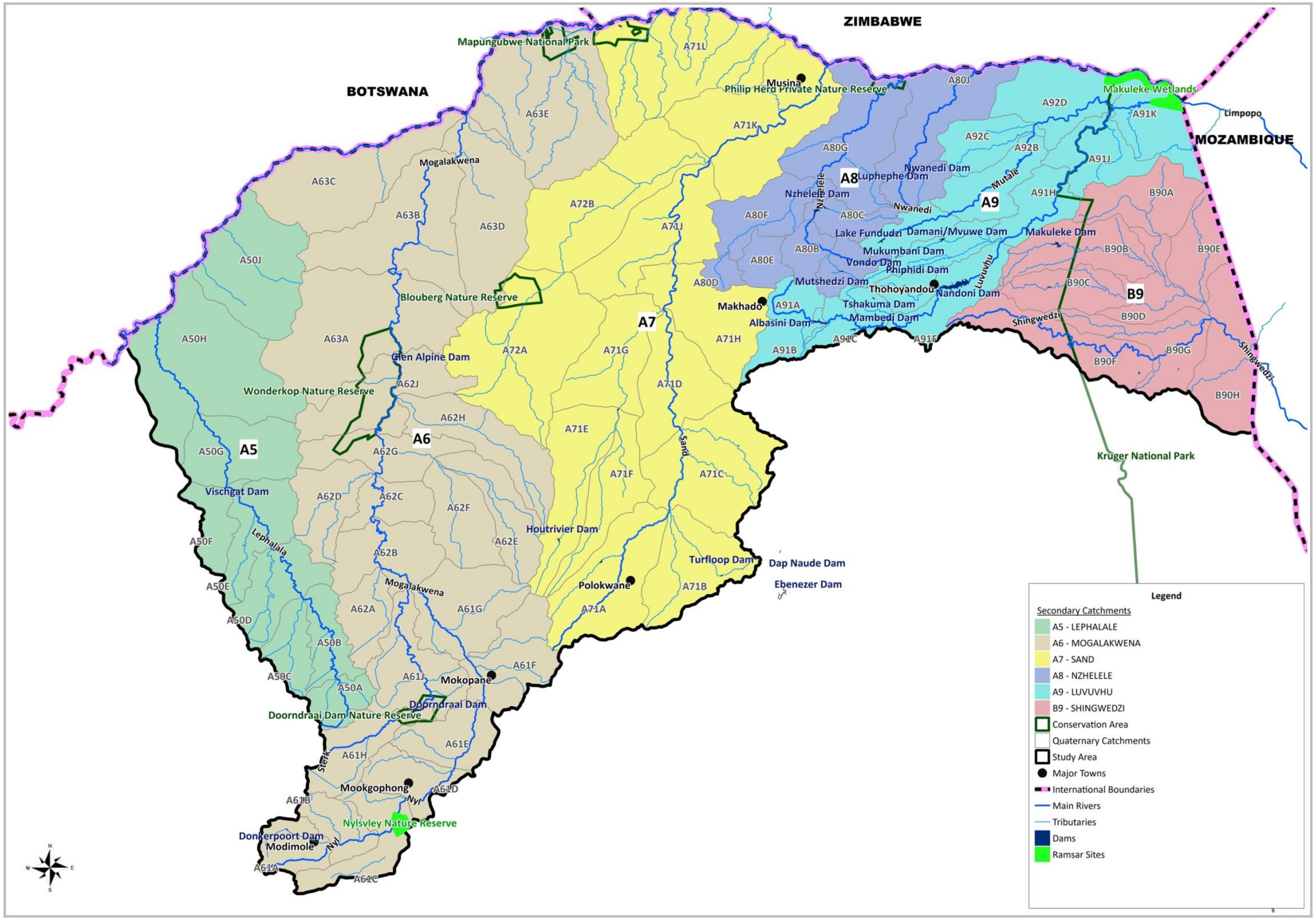

Figure E1: Map of the study area

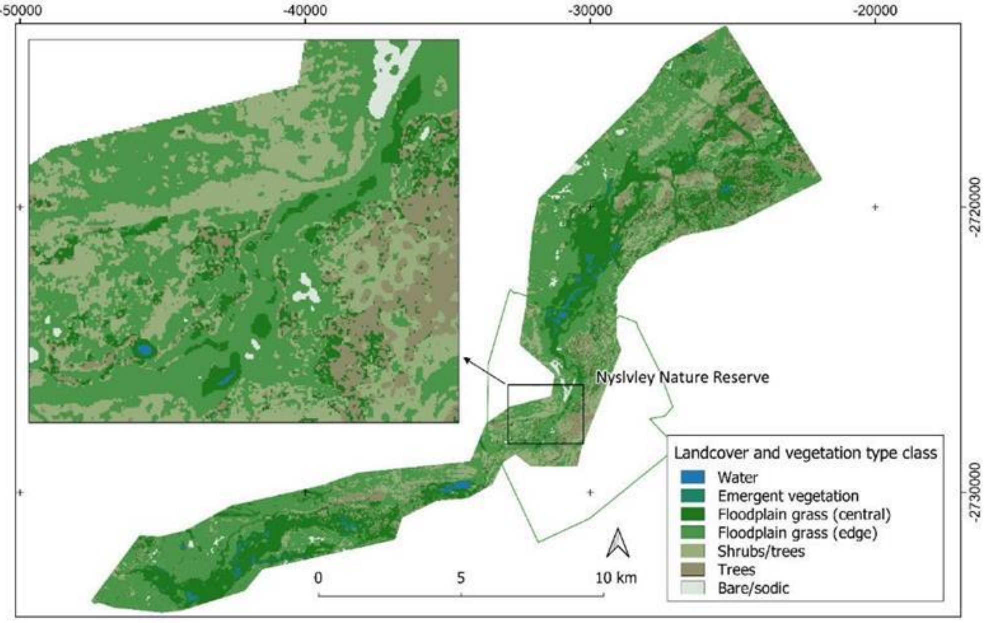

Figure E2: Vegetation map of the Nyl River floodplain derived from Sentinel 2 10-m spatial resolution multispectral imagery (3 September 2022); CRS is Hartebeeshoek94 Lo29

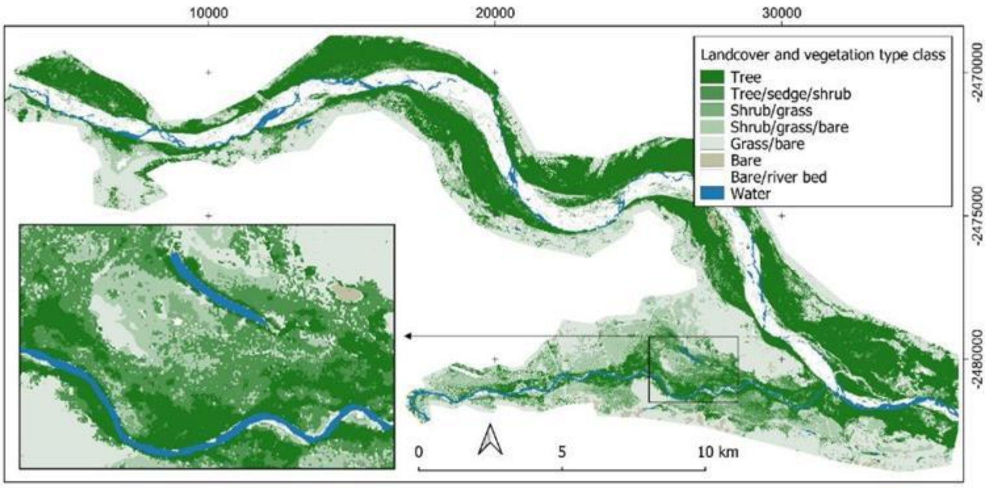

Figure E3: Vegetation map of the Luvuvhu River floodplain, derived from 10-m spatial resolution multispectral imagery (23 September 2022); inset shows the Luvuvhu River and Nwambi Pan; CRS is Hartebeeshoek94 Lo31

Nyl River floodplain

The Nyl River floodplain was divided into three EWR zones (**Figure E4**):

- 15_Nylsvley 1 – upstream of Nylsvley Nature Reserve.
- 16_ Nylsvley 2 –Nylsvley Nature Reserve.
- 17_Nylsvley 3 – downstream of Nylsvley Nature Reserve.

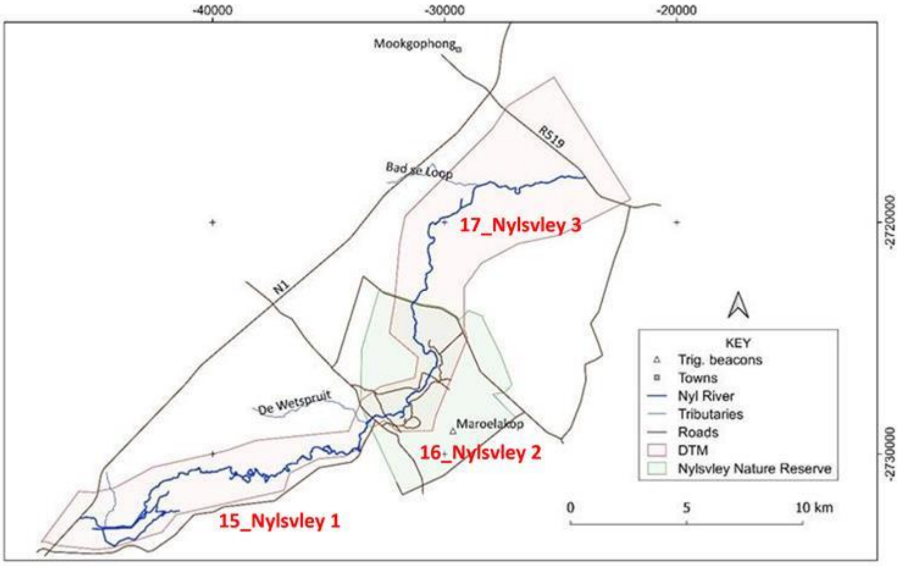

Figure E4: The 3 EWR zones of the Nyl River floodplain

A list of wetland indicators that represent the Nyl River floodplain and reasons for their selection are shown in **Table E1**.

Table E1: Wetland indicators of the Nyl River floodplain and reasons for their selection

Indicator	Reason for selection	EWR zone		
		15	16	17
Aquatic vegetation	Aquatic plants are important as food for many animals and provide habitat for aquatic organisms and some improve water quality. They have medicinal and food value for humans.	X	X	X
Reeds	Reeds are eaten by domestic and wild herbivores and provide important habitat for aquatic invertebrates.	X	X	X
Central floodplain grass	Central floodplain grasses are an important source of food for birds and mammals and as breeding grounds for birds, fish, amphibians and mammals. They are also grazing areas for domestic livestock and play a role in flood attenuation and erosion control.	X	X	X
Edge floodplain grass	Edge floodplain grasses are important grazing areas for wildlife and domestic livestock. They also provide habitat for wildlife when the central floodplain grasses are inundated. They play a role in flood attenuation and erosion control.	X	X	X
Shrubs and trees	Shrubs and trees grow on the edges of the floodplain or on raised mounds and are important habitat for a variety of floodplain animals.	X	X	X
Coenogrionidae	Coenogrionids inhabit marginal vegetation in slow flowing water and are an important food source for birds and fish.	X	X	X
White-breasted cormorant	White-breasted cormorants feed on fish in open water (pools, pans, backwaters and the channel). They were selected to represent all birds that feed in open water because they are very abundant at Nylsvley.	X	X	X
White-faced duck	White-faced ducks spend time on open water and in marginal vegetation, are omnivorous eating seeds, tubers and invertebrates (insects, crustaceans and worms). They were selected to represent all dabbling waterfowl (ducks and teals) because they were very abundant at Nylsvley.	X	X	X
Water buck	Waterbuck inhabit grasslands and are highly dependent on water to maintain their hydration. They also favour reeds as one of their food items. They were selected because they are one of the flagship water-dependent antelope at Nylsvley.	X	X	X
Floodplain dependent fish	Floodplain dependent fish move onto the floodplains to breed and the inundated floodplains provide nursery areas for juvenile fish.	X	X	X

The Present Ecological Status (PES) of the Nyl River floodplain was determined using the WET-Health Level 1 assessment for Hydrology, Geomorphology, Water quality and Vegetation, and for the whole floodplain (**Table E2**). The PES for the biota was derived from a combination of two or three of the floodplain driver scores (as appropriate) and adjusted based on other available information (local knowledge, literature, data) if necessary and observations in the field (**Table E3**).

Table E2: Overall PES of the Nyl River floodplain

Components	Method used for assessment	PES% Score	Ecological Category
Hydrology PES	WET-Health Hydrology Module	65 %	C
Geomorphology PES	WET-Health Geomorphology Module	73 %	C
Water quality PES	Wetland-IHI Water Quality Module	79 %	B/C
Vegetation PES	WET-Health Vegetation Module	58 %	C/D
Overall Wetland PES	WET-Health default weightings	65 %	C

Table E3: Derived PES for the biota on the Nyl River floodplain

<table>
<tr><th>Discipline</th><th>Indicator in DRIFT</th><th>WET-Health drivers combined</th><th colspan="2">Ecological category</th></tr>
<tr><td>Invertebrates</td><td>Coenagrionids</td><td>Hydrology (C), water quality (B/C)</td><td colspan="2">B/C raised to a B</td></tr>
<tr><td>Fish</td><td>Floodplain dependent fish</td><td>Hydrology (C), geomorphology (C), water quality (B/C)</td><td colspan="2">C</td></tr>
<tr><td rowspan="2">Birds</td><td>White-faced duck</td><td>Hydrology (C), water quality (B/C), vegetation (C/D)</td><td>C</td><td rowspan="2">C raised to a B/C</td></tr>
<tr><td>White-breasted Cormorant</td><td>Vegetation (C/D), fish (C)</td><td>C</td></tr>
<tr><td>Mammals</td><td>Waterbuck</td><td>Hydrology (C), water quality (B/C), vegetation (C/D)</td><td colspan="2">C raised to a B/C</td></tr>
</table>

There are no future developments planned in the Nyl River catchment that are expected to affect the PES conditions of the Nyl River floodplain, so the analysis tested combinations of alternate wet and dry years to demonstrate how the DRIFT model responded to the frequency of floods and the extent and duration of floodplain inundation. The overall integrity of the Nyl River floodplain is expected to drop from a C category under the Present ecological scenario, to a D/E under the Dry scenario, a D under the 6d1w (six dry years, one wet year) scenario, a D under the 4d1w1d1w (four dry, one wet, one dry, one wet) scenario and a C/D under the 2d1w-20W (two dry, one wet, and a big wet year every approximately 20 years) scenario (**Figure E5**).

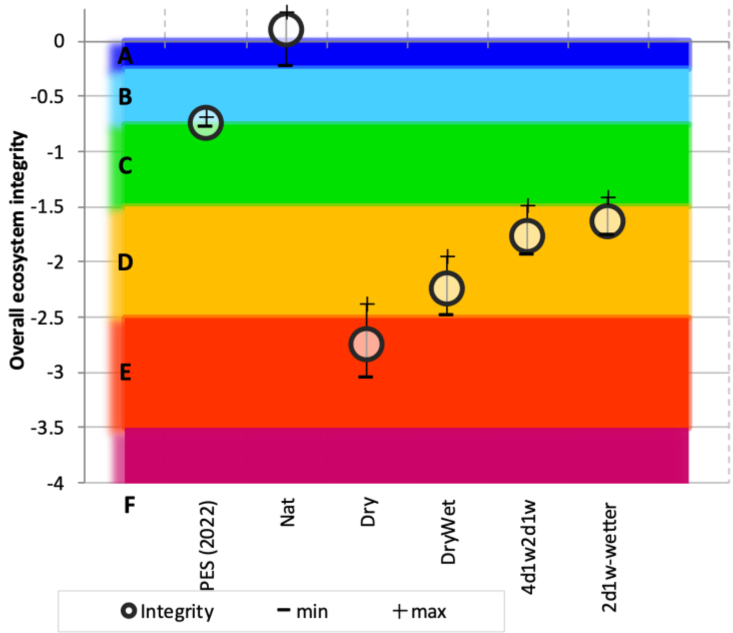

Figure E5: Overall ecosystem integrity of the Nyl River floodplain under the scenarios.

The EWR for the Nyl River floodplain is to maintain a PES (2022) Ecological Category C and was derived from discharges from the Olifantspruit and Nyl rivers. Other tributaries also contribute to the maintenance of the floodplain. It comprises lowflows, small and large floods in the Nyl at the N1 and Olifantspruit Rivers and the frequency and duration of inundation of vegetation on the floodplain.

Luvuvhu River floodplain

There are six EWR sites on the Luvuvhu River floodplain (**Figure E6**):

- 18_Luvuvhu2 – is an important breach point where the Luvuvhu River overtops its banks and floods the floodplain.
- 19_Nwambi Pan – is a perennial, or near-perennial pan on the northern Luvuvhu floodplain that supports tall floodplain trees, crocodiles and a large pod of hippos and is flooded by both the Luvuvhu and Limpopo Rivers.
- 20_Mambvumbvanyi Pan – is a seasonal pan on the northern Luvuvhu floodplain that supports Fever tree forests, seasonal emergent floodplain vegetation and is flooded by both the Luvuvhu and Limpopo rivers.
- 21_Hapi Pan – is a perennial, or near-perennial pan on the southern Luvuvhu floodplain that supports crocodiles and hippos and is filled by flooding from the Luvuvhu River and lateral inputs from ephemeral drainage channels.
- 22_Tlangelani Pan – is a seasonal pan on the southern Luvuvhu floodplain that supports floodplain grasslands and is flooded by both the Luvuvhu and Limpopo rivers.
- 23_Luvuvhu3 - is a river site on the Luvuvhu River at the confluence with the Limpopo River that is important because deep pools support hippos and crocodiles in the dry season and droughts.

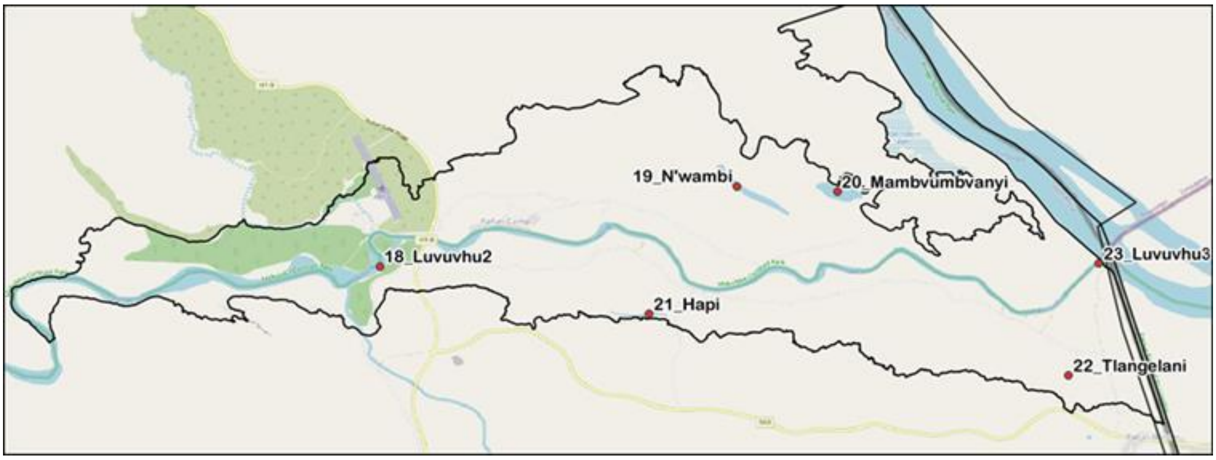

Figure E6: The 6 EWR sites on the Luvuvhu River floodplain

A list of indicators that represent the Luvuvhu River floodplain and the reasons for their selection are shown in **Table E4.**

Table E4: Wetland indicators of the Luvuvhu River floodplain and the reasons for their selection

Indicator	Reason for selection	Site Numbers					
		18	19	20	21	22	23
Hippo pool	A large pool at the junction of the Luvuvhu and Limpopo rivers that supports hippopotami and crocodiles in the dry season.						X
Riparian vegetation	Riparian plants, e.g., marginal reeds and trees, grow on the riverbanks and are habitat for riparian fauna. They also stabilise banks and attenuate floods.	X					X
Floodplain vegetation	Floodplain forests, floodplain shrubs and floodplain grasslands, all variously associated with the floodplain and pans, and all of which provide habitat and food for wildlife.		X	X	X	X	
White-faced duck	Represents dabbling ducks and teals that occur on the pans feeding on seeds, tubers and invertebrates (insects, crustaceans and worms); e.g., the Yellow-billed Duck and the African Black Duck.		X	X*	X	X	
African fish eagle	Represents carnivorous birds that nest in and hunt from tall riparian trees. It eats fish, rodents and other small animals. This group includes the Pied and Malachite Kingfishers.	X	X	X*	X	X	X
Tolerant fish	Fish that are tolerant to a range of flow and water quality variables and are able to persist when trapped in the pans.	X	X	X*	X	X	X
Crocodile	Crocodiles are aquatic reptiles, an apex predator that mostly feed on fish, but take any prey. They need permanent water and sandy banks for nesting.	X	X	X*	X	X	X
Hippopotamus	Hippos are semi-aquatic mammals that need pools deep enough in which to submerge during the day and floodplain grasslands to graze at night.	X	X	X*	X	X	X

The Present Ecological Status (PES) of the Luvuvhu River floodplain was determined using the WET-Health Level 1 assessment method that generates an Ecological Category for Hydrology, Geomorphology, Water quality and Vegetation (**Table E5**). The PES for the animal indicators was derived from a combination of two or three of the floodplain driver scores (as appropriate) and adjusted based on other available information (local knowledge, literature, data) and observations in the field if necessary (**Table E6**).

Table E5: Overall PES for the Luvuvhu River floodplain

Components	Method used for assessment	PES% Score	Ecological Category
Hydrology PES	WET-Health Hydrology Module	70 %	C
Geomorphology PES	WET-Health Geomorphology Module	90 %	A/B
Water quality PES	Wetland-IHI Water Quality Module	71 %	C
Vegetation PES	WET-Health Vegetation Module	87 %	B
Overall Wetland PES	WET-Health default weightings	80 %	B/C

Table E6: Derived PES for the biota on the Luvuvhu River floodplain.

<table>
<tr><th>Discipline</th><th>Indicator in DRIFT</th><th>WET-Health drivers combined</th><th>Ecological category</th><th>Adjusted EC</th></tr>
<tr><td>Fish</td><td>Tolerant fish</td><td>Hydrology (C), geomorphology (A/B), water quality (C)</td><td>B/C</td><td>B/C</td></tr>
<tr><td rowspan="2">Birds</td><td>White-faced duck</td><td>Hydrology (C), water quality (C), vegetation (B/C)</td><td>B/C</td><td rowspan="2">B/C</td></tr>
<tr><td>African fish eagle</td><td>Vegetation (B), fish (B/C)</td><td>B/C</td></tr>
<tr><td rowspan="2">Wildlife</td><td>Hippopotami</td><td>Hydrology (C), water quality (C), vegetation (B)</td><td>B/C</td><td rowspan="2">B</td></tr>
<tr><td>Crocodiles</td><td>Hydrology (C), geomorphology (A/B), water quality (C), fish (B/C)</td><td>B</td></tr>
</table>

Water resource developments are planned in the Luvuvhu River, and its incremental tributary the Mutale River, upstream of the floodplain. The outcomes of these developments were tested in the DRIFT model under a Future1 flow and a Future2 scenario, with the same developments under climate change. The four scenarios assessed were:

- PES (2022), which used the climatic period of 1955-2011 with human influences such as water-resource developments, population and land use at 2022 levels.
- Naturalised, which used the climatic period of 1955-2011 with human influences such as water-resource developments, population and land use at *c*. 1900 levels.
- Future1, which overlaid 2050 water resource developments on PES.
- Future2, which overlaid a dry future climate scenario onto Future1.

The predictions are that the overall integrity of the Luvuvhu River floodplain is expected to drop from a B/C category under the Present Ecological State (2022) scenario to a C under the Future1 scenario and a C/D under Future2 (**Figure E7)**.

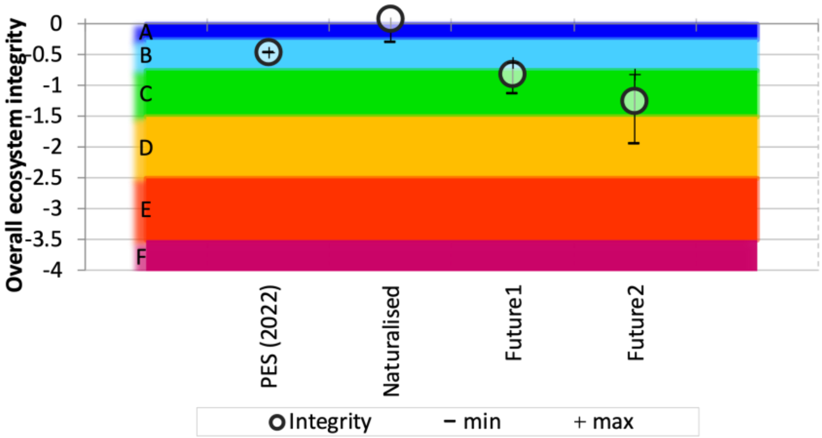

Figure E7: The overall ecosystem integrity of the Luvuvhu River floodplain under the four flow scenarios

The change in each discipline is indicated in **Table E7** that shows vegetation dropping one full category from a B to a C under Future1, fish remaining the same, and birds and wildlife dropping a half category each from a B/C to a C category.

Table E7: Predicted changes in ecological category of the indicators to the four flow scenarios

	PES (2022)	Naturalised	Future1	Future2
Vegetation	B	A	C	D
Fish	B/C	B	B/C	C
Birds	B/C	A	C	C/D
Wildlife	B	A	B/C	C
Overall	**B/C**	**A**	**C**	**C/D**

Two options for EWRs are provided for the Luvuvhu River floodplain that comprise lowflows, small and large floods in the Luvuvhu River to maintain the PES (2022) B/C category of the floodplain prior to development, derived from the PES flow scenario, and a C category post-development, derived from the Future1 flow scenario.

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1 INTRODUCTION

1.1 Background

The Department of Water and Sanitation (DWS), Chief Directorate (CD): Water Ecosystems Management (WEM) initiated a three-year study, extended to a fourth year, to Determine Water Resource Classes, the Reserve and Resource Quality Objectives (RQO) for Secondary Catchments A5-A9 in the Limpopo Water Management Area (WMA 1) and Secondary Catchment B9 in the Olifants Water Management Area (WMA 2). This project aligns with the Department's mandate to protect water resources as stipulated in Chapter 3 of the National Water Act.

The Resource Directed Measure (RDM) tools implemented in these catchments aim to ensure sustainable utilisation of water resources to meet the ecological, social and economic needs of the communities dependent on them and provide a mechanism against which the objectives set can be monitored for compliance.

1.2 Objectives of the study

The overall objective of the study is to classify and determine the Reserve and RQOs for all significant water resources in secondary catchments (SCs) A5-A9 in the Limpopo WMA and SC B9 in the Olifants WMA.

The Scope of Work (SoW) as stipulated in the Terms of Reference calls for:

- Implementation of the Water Resources Classification System (WRCS, Dollar *et al*. 2006), as required in Regulation 810 in Government Gazette 33541, and classify all significant water resources in the Limpopo WMA (SCs A5-A9) and Olifants WMA (SC B9).
- Determination of the water quantity and quality components of the Reserve for groundwater, rivers and wetlands.
- Determination of the RQOs using the DWS 'Procedures to Determine and Implement Resource Quality Objectives' (DWAF 2011).

The determination of the water quantity and quality components of the Ecological Reserve comprises a series of steps including EcoCategorisation, which is the process of determining the status of the groundwater, and the ecological status of the study rivers and wetlands, and the assessment of a range of Ecological Water Requirements (EWRs[1]) needed to support different levels of ecological health in the rivers and wetlands (Adams *et al*. 2016). The information from the EWR assessment is then used in the implementation of the WRCS, where stakeholders consider the implication of existing and planned water-resource developments on the water available for the rivers and wetlands and associate the predicted impacts on their ecological category (**Table** 1.1**)**. In the WRCS, one EWR and its associated ecological category will be chosen for a river or wetland reach. This becomes the Ecological Reserve. RQOs are numerical and/or descriptive statements of the biological, chemical and physical attributes that characterise a river or wetland for the level of protection defined by the ecological category selected in the WRCS.

[1] The quality, quantity and timing of flow to support ecosystem function (Adams *et al*. 2016).

Table 1.1: Definitions of the ecological categories (Kleynhans 1996)

Ecological Category	Description of habitat
A	Still in a natural condition
A/B	
B	Slightly modified. A small change in natural habitats and biota has taken place but the ecosystem functions are essentially unchanged from natural
B/C	
C	Moderately modified from natural. Loss and change of natural habitat and biota have occurred, but the basic ecosystem functions are still unchanged
C/D	
D	Largely modified. A large loss of natural habitat, biota and basic ecosystem functions has occurred
D/E	
E	Seriously modified. The loss of natural habitat, biota and basic ecosystem functions is extensive
E/F	
F	Critically/Extremely modified. The system has been critically modified with an almost complete loss of natural habitat and biota. In the worst instances, basic ecosystem functions have been destroyed and the changes are irreversible

1.3 Purpose of this report

This report is the Wetland Assessment (Volume 2): Ecological Water Requirements (EWR) Report. It describes the hydro-ecological assessments of the Nyl and Luvuvhu River floodplains and the outcomes of the scenarios analysed to determine EWRs. It is the second report dealing with wetland assessment in the study:

- Wetland Assessment Volume 1 – Ecostatus and Priority Wetlands.
- **Wetland Assessment (Volume 2): Hydrodynamic modelling and Ecological Water Requirements of the Nyl and Luvuvhu River Floodplains Report.**

In this report:

- Section 2 describes the overall approach to the wetland EWR assessment.
- Section 3 describes the vegetation mapping.
- Section 4 describes the hydrodynamic modelling
  - Section 4.1 gives background information, describes data collection and analyses, development of the hydrodynamic model, and modelling results for the Nyl River floodplain
  - Section 4.2 gives background information, describes data collection and analyses, development of the hydrodynamic model, and modelling results for the Luvuvhu River floodplain.
- Section 5 describes the Nyl River floodplain; the EWR zones, Present Ecological Status, description of scenarios, outcomes from the scenario analysis, hydrodynamic functioning and Ecological Water Requirements.
- Section 6 describes the Luvuvhu River floodplain; the EWR sites, Present Ecological Status, description of scenarios, outcomes from the scenario analysis, hydrodynamic functioning and Ecological Water Requirements.

1.4 Study area

The study area encompasses the Limpopo WMA SC A5 – A9 and the Olifants WMA SC B9 (**Figure** 1-1). The area spans six river catchments: Lephalala, Mogalakwena, Sand, Nzhelele and Luvuvhu rivers in the Limpopo WMA and the Shingwedzi River in the Olifants WMA.

The rivers in the Limpopo WMA are part of the transboundary Limpopo River Basin, which is shared by South Africa, Botswana, Zimbabwe and Mozambique. The mainstem Limpopo River falls outside of the scope of work (**Section 1.2**), as it is a transboundary watercourse that falls under the ambit of the Limpopo River Commission (LIMCOM) and its four member states, which have already completed an EFlows assessment (O'Brien *et al*. 2022) that is currently being reviewed and updated (as at January 2024).

According to the latest national wetland map (National biodiversity assessment; van Deventer *et al.*, 2018) there are almost 77 000 Ha of wetlands in the study area (**Figure** 1-2**)**. This includes two RAMSAR sites, the Nylsvley floodplain and the Makuleke wetland complex associated with the Luvuvhu and Limpopo rivers. Each of these is covered in detail in this report. In addition, volume 1 of this study (DWS, 2024) outlines the outcomes of the wetland prioritisation process in the study area, with the following being highlighted as the highest priority:

- Luvuvhu Floodplain (Makuleke)
- Nyl River Floodplain
- Wonderkrater
- Nyl Pans
- Maloutswa Floodplain (Mapungubwe)
- Kolope Wetlands
- Lake Fundudzi
- Mutale Wetlands
- Mokamole wetlands – a tributary of the Mogalakwena River
- Malahlapanga (Peat dome)
- Bububu wetlands – a tributary of the Shingwedzi River

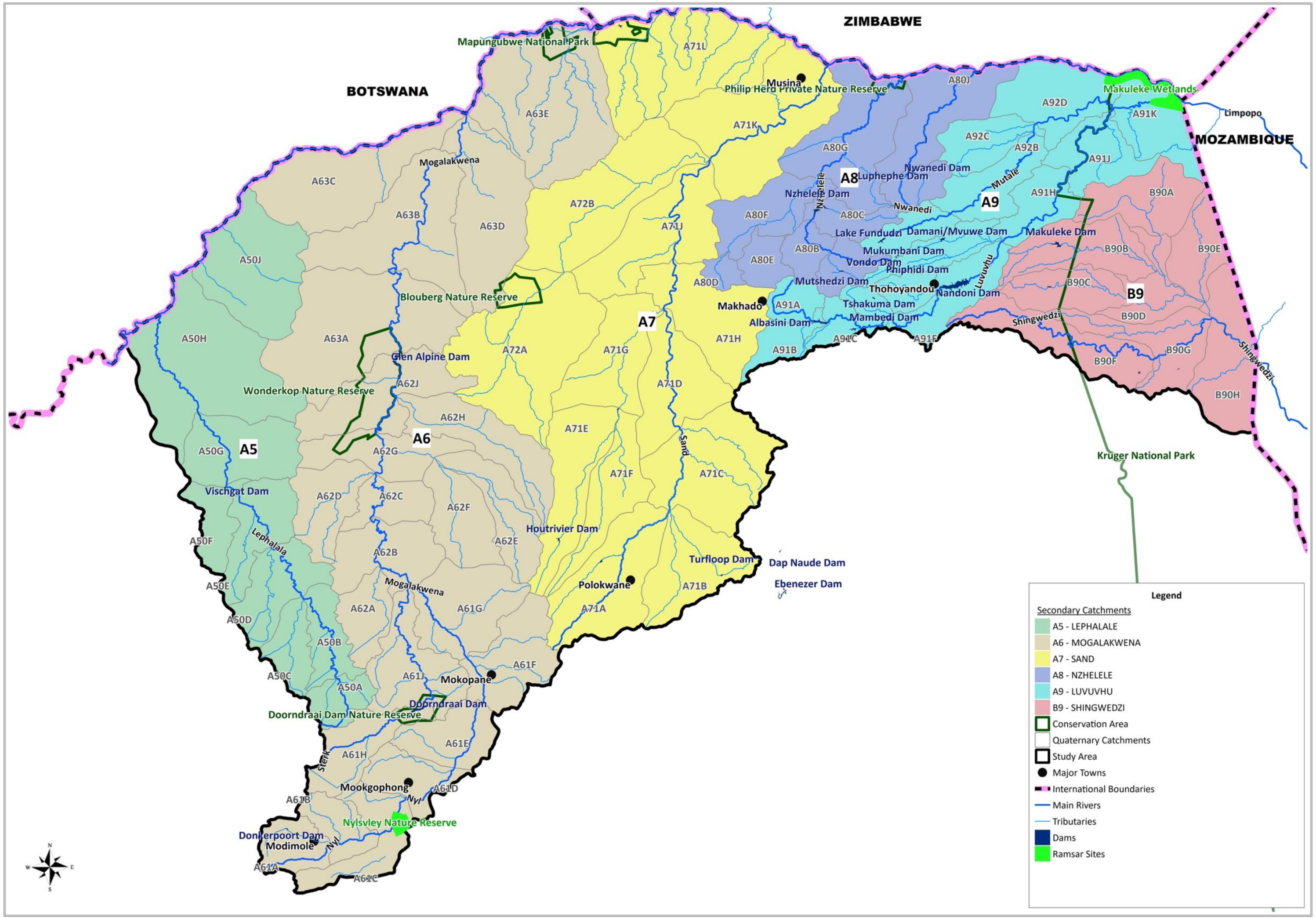

Figure 1-1: Map of the study area

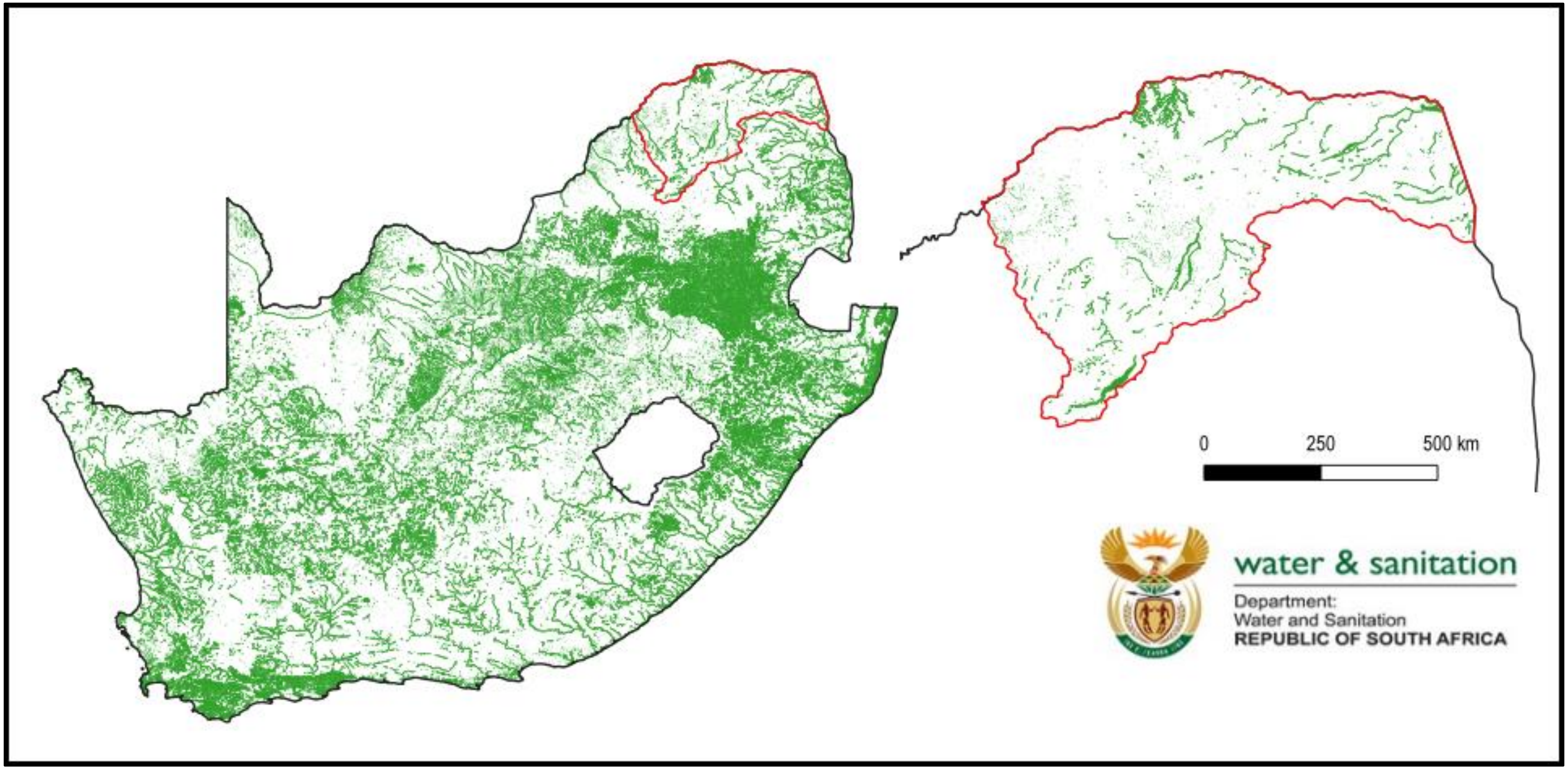

Figure 1-2: Wetlands within South Africa (left) and the study area (right; 2018 updated wetland map 5; van Deventer *et al.*, 2018).

2 APPROACH TO WETLAND EWR

2.1 Introduction

Investigations of the EWRs for floodplain wetlands require a model to predict the extent and duration of flooding on the floodplains, and an understanding of how this related to vegetation patterns. Thus, the bulk of the effort in the Nyl and Luvuvhu River floodplain EWR assessments was focussed on developing these two sets of information.

Accordingly, the approach adopted for the EWR assessments was to:

- create vegetation maps and groundtruth the mapped plant communities (**Section 3**).
- focus on developing a reliable and efficient hydrodynamic model to predict the extent and duration of flooding on the floodplains (**Section 4**).
- review the literature on key biota and undertake an EcoStatus assessment based on existing information (**Sections 5 and 6**).
- populate a DRIFT model for each floodplain that represents a sound understanding of the hydro-ecological functioning.
- evaluate the ecological outcome of a future development or climate change scenario as appropriate.

The resulting assessment equates to an Intermediate Level confidence. This is based on:

- the hydrodynamic models underpinning the assessments.
- vegetation mapping with ground-truthing.
- extensive information on flow/flood relationships for river and floodplain organisms used to populate the DRIFT models.

That said, the modelling and the predictions should be evaluated with due consideration of the underlying assumptions and limitations of the assessment (**Section 2.5**).

2.2 Overview of DRIFT

DRIFT is a model and database of eco-social information and knowledge used to predict potential changes to the floodplains as a result of human pressures, such as water-resource developments and climate change. Since the two floodplains are in conservation areas the social benefits are derived from ecotourism. This is directly related to the ecological integrity of the two floodplains and their biota, so social benefits are inferred and not modelled in DRIFT.

2.2.1 Modules

DRIFT comprises three modules (**Figure** 2-1**)**:

1. Setup
2. Knowledge Capture
3. Analysis.

These three modules, with all their components, are presented within the cream block at the bottom of **Figure** 2-1. The elements that provide input to and outputs from these are indicated in the area above the cream block.

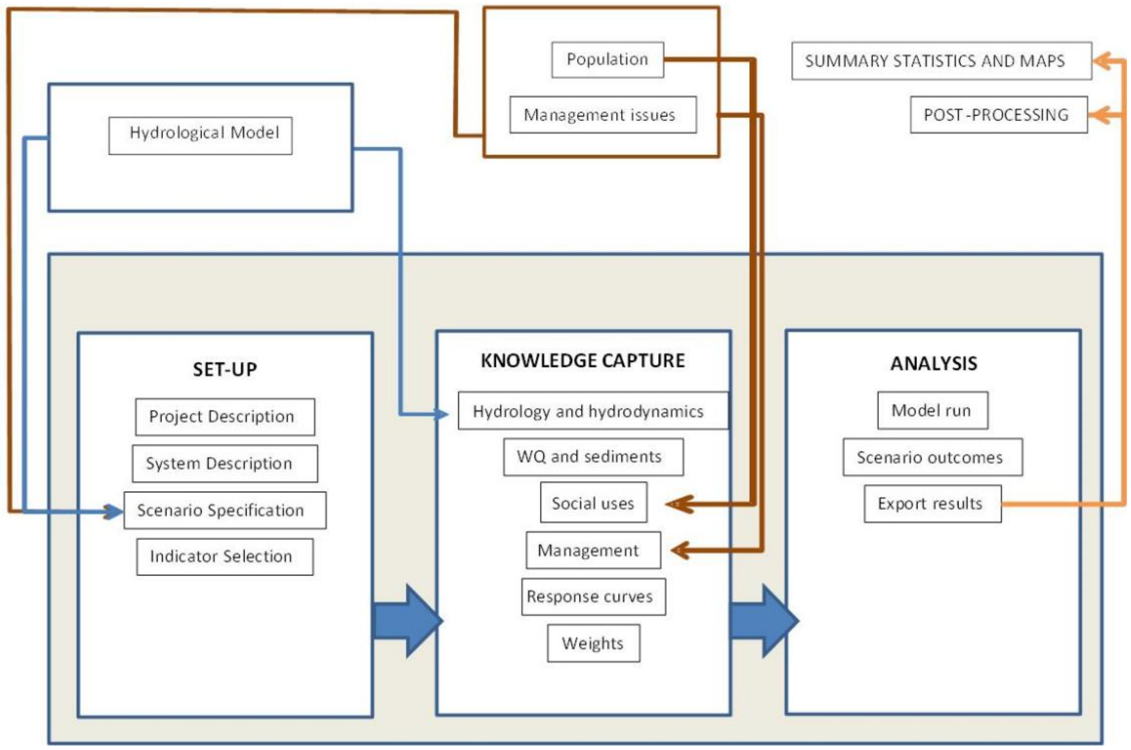

Figure 2-1: Arrangement of modules in DRIFT (light-brown shading) and inputs/outputs from/to external models/data sources

The first two modules deal with the setup, population and calibration of the hydro-ecological relationships that will be used to predict the ecosystem response to potential development actions. The third module is used to generate results once the first two modules have been configured, and to export the output data detailing the predictions for the configurations under consideration to MS Excel for post-processing and reporting.

2.2.2 Disciplines

The hydrodynamic modelling is described in detail in **Chapter 4**. The floodplain ecosystems were represented by six disciplines:

- Vegetation
- Invertebrates
- Fish
- Birds
- Herpetofauna
- Mammals.

2.2.3 Hydro-biological flow seasons

DRIFT uses four hydro-biological flow seasons:

- Dry Season (Dry). Flows are much less than the annual average and there is relatively little *natural* flow variability from day to day.
- Transition Season 1 (T1). A time of transition between the end of the Dry Season and the start of the Flood Season. Flows increase but not necessarily rapidly. A number of spates or

'freshets' might typically signify a number of false starts to the Flood Season, with flows receding again after each one.

- Flood/Wet Season (Flood). This is initially characterized by several periods of accelerated rates of increasing flow until the annual peak discharge is reached. There may be a number of pulses in this process but overall, there is a clear single flood-pulse hydrograph.
- Transition Season 2 (T2). A second transition season between the end of the Flood Season and the start of the Dry Season, during which time the rate of flow recession remains higher than in the Dry Season. In some years there may be late but relatively minor spate events.

2.2.4 Indicators and links

The input data for each floodplain are summarised in **Sections 5.3** for the Nyl River floodplain and **Section 6.3** for the Luvuvhu River floodplain. Discipline-specific indicators and the links between driving and responding indicators were derived by the EWR team (**Sections 5.4** and **6.4**). Changes in the ecosystem indicators were predicted through response curves in DRIFT.

The first sets of data produced were the PES (2022) and Naturalised scenarios against which the DRIFT was calibrated. Thereafter, simulated time-series over the same period were produced for the scenarios (**Sections 5.5** and **6.5**), and relative change linked to the scenarios was reported relative to PES (2022).

2.2.5 Ecological indicators

Ecological indicators are a set of indicators that represent the floodplain ecosystems. They are deemed to be sensitive to a change in the driver indicators (Sections 5.3 and 6.3) by changing in one of the following ways:

- abundance/size, e.g., fish.
- extent (area), e.g., cover of riparian tree community on upper dry bank.
- concentration, e.g., sediments and nutrients.

Indicators were selected in each discipline, with due consideration of their relevance for other disciplines. For instance, the vegetation indicator 'central floodplain grass' at Nylsvley was selected because it provides important seasonal food reserves for granivorous birds and is also grazed. The indicators, the reasons for their selection and the driving links are discussed in **Sections 5.4** and **6.4.**

The value of an indicator may change with scenarios, and in doing so, drive other indicators to change. For instance, responders to one driver (e.g., central floodplain grass declining when inundation is poor) can become drivers themselves (e.g., change in central floodplain grass affects some bird and mammal species), thus driving further change (e.g., reduction in fecundity). The simplified linkages between disciplines are shown in **Figure** 2-2 and **Figure** 2-3. Each line in **Figure** 2-2 and **Figure** 2-3 represents a response curve drawn by the specialists and housed in the DRIFT DSSs; along with a motivation for its shape.

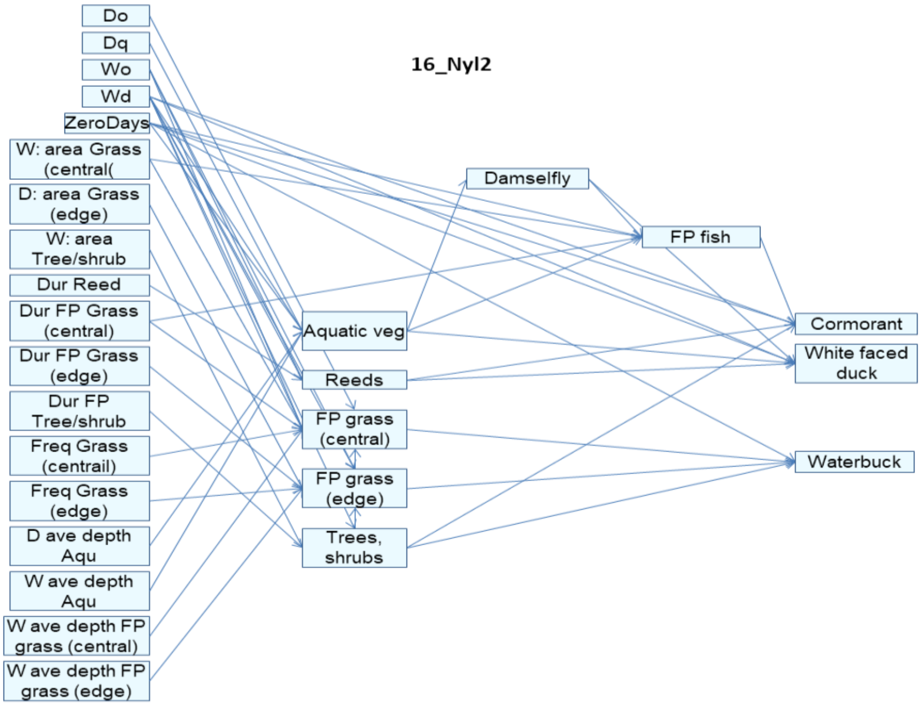

Figure 2-2: Discipline-level assessment framework for EWR sites in DRIFT-Nylsvley. Each line is represented by a response curve

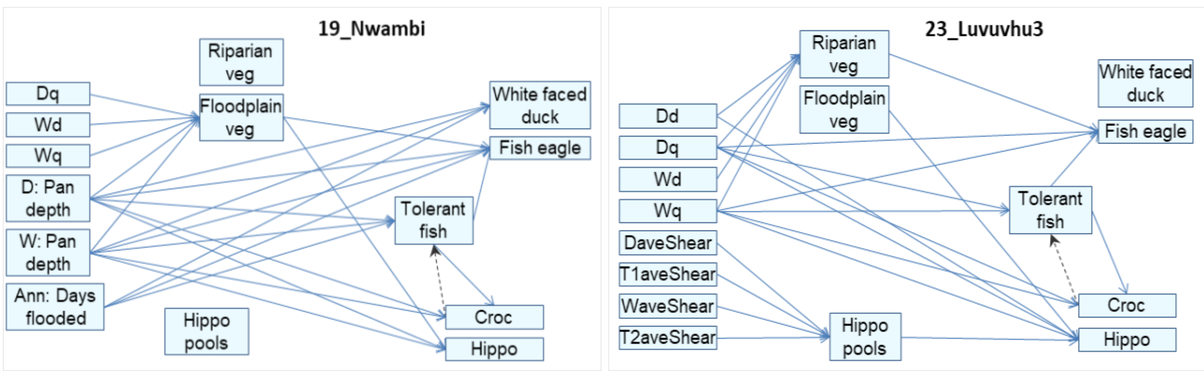

Figure 2-3: Discipline-level assessment framework for EWR sites in DRIFT-Luvuvhu. Each line is represented by a response curve

The DRIFT databases thus form a knowledge base set up by the EWR specialists using existing knowledge and understanding about the functioning of the aquatic ecosystems. In this study the database was interrogated to analyse a suite of EWR scenarios, but it is also available to test other scenarios as part of future studies or planning initiatives.

The list of indicators used for each discipline is provided in **Sections 5.4** and **6.4**. These were selected because of their importance in the functioning of the ecosystem and, in the case of the fauna, because they represent wider groups of species and/or species of particular conservation concern.

2.3 Response curves

Response curves are housed in DRIFT and depict the relationship between an ecological indicator and a driving variable (e.g., wet season duration). A response curve for the relationship between central floodplain grass and the duration of the wet season is shown in **Figure** 2-4**.**

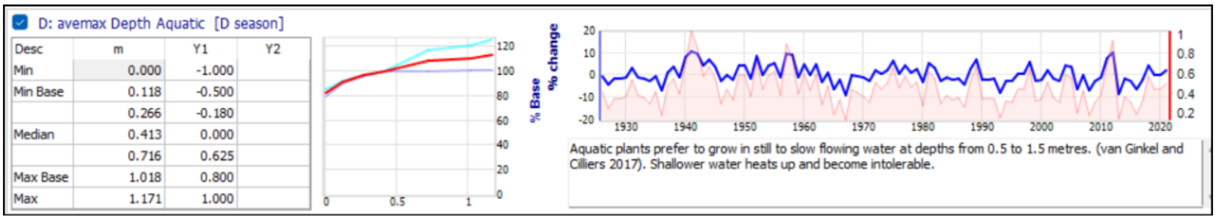

Figure 2-4: A snap-shot from DRIFT-Nylsvley showing one of the vegetation response curves and explanations for aquatic vegetation at 15_Nyl

In **Figure** 2-4**,** the red line in the first graph is the mean response, and the light blue and darker blue lines represent the uncertainty (upper and lower limits). In the second graph (time-series), the solid pink series shows the annual values for the linked indicator, e.g., wet season duration. The blue lines in these time-series graphs show the modelled annual response of central floodplain grass to the present state variations for the linked indicator only, i.e., excluding any responses to other drivers. These variations are around the mean PES values of 100% for the indicator.

The units on the x-axis depend on the driving indicator under consideration. For instance, for the abundance of shrubs and trees (**Figure** 2-4), these are in percentages greater or less than PES. The y-axis may refer to abundance as in **Figure** 2-4, but also to other measures such as concentration or area, depending on the indicator. Response curves were constructed using severity ratings (**Table** 2.1).

Each response curve is accompanied by an explanation of its importance and the relationship it depicts. For the example in **Figure** 2-4, the explanation for the central floodplain grass response curve reads as follows: "*Oryza is clonal and relies on vegetative reproduction rather than viable seed and it is therefore important the rhizomes are replenished with each flood response since old rhizomes don't store well (Marneweck pers. com. 2023). When dormant rhizomes respond to flooding, they spend the first period producing new rhizomes first (about 30 to 45 days of inundation), only then begin to allocate resources to new tillers, which need to emerge to produce stolons and complete its life cycle in about 150 days (optimum flooding duration). Longer inundation allows rhizomes to establish deeper and improve resilience (Marneweck pers. com. 2023).*"

Table 2.1: DRIFT severity ratings and their associated gains and losses – a negative score means a loss in abundance relative to PES, a positive means a gain

Severity rating	Severity	% abundance change
5	Critically severe	501 % gain to ∞ up to pest proportions
4	Severe	251-500 % gain
3	Moderate	68-250 % gain
2	Low	26-67 % gain
1	Negligible	1-25 % gain
0	None	no change
-1	Negligible	80-100 % retained
-2	Low	60-79 % retained
-3	Moderate	40-59 % retained
-4	Severe	20-39 % retained
-5	Critically severe	0-19 % retained includes local extinction

The response curves do not address any of the scenarios directly. The curves are drawn for a range of possible changes in each linked indicator, regardless of what is expected to occur in any of the scenarios. For this reason, some of the explanations refer to conditions that are unlikely to occur under any of the water-resource development scenarios but are needed for completion of the response curves. In addition, each response curve assumes that all other driving indicators are at PES.

The response curves are used to evaluate scenarios by taking the value of the flow indicator for any one scenario and reading off the resultant values for the ecological indicators from their respective response curves. For each year of the hydrological record, and for each ecological indicator, the severity rating corresponding to the value of a driving indicator is read off its Response Curve and converted to a percentage change. The severity ratings for each driving indicator are then combined to produce an overall change in abundance for each season, which provide an indication of how abundance, area or concentration of an indicator is expected to change under the given flow conditions over time, relative to the changes that would have been expected under PES conditions.

2.4 EWR assessment method

The seven-step DRIFT process **(Figure** 2-5) (King *et al*. 2003; Joubert *et al*. 2022; **Section 2.2**) was used to organise three main kinds of hydro-ecological information for the two floodplain wetlands: collated and collected data; relevant data in the international scientific literature and project reports, and; expert opinion from the experienced team of river and wetland scientists. This knowledge base was then used to:

- select the ecosystem indicators that represent the floodplain wetlands;
- assess the ecological condition and trends of the ecosystem indicators in each of the scenarios, by predicting their change in abundance/area/concentration (relative to a PES (2022));
- set up two DRIFT models:
    - DRIFT-Nylsvley
    - DRIFT-Luvuvhu
- predict the overall ecological condition of the floodplain wetlands under each scenario.

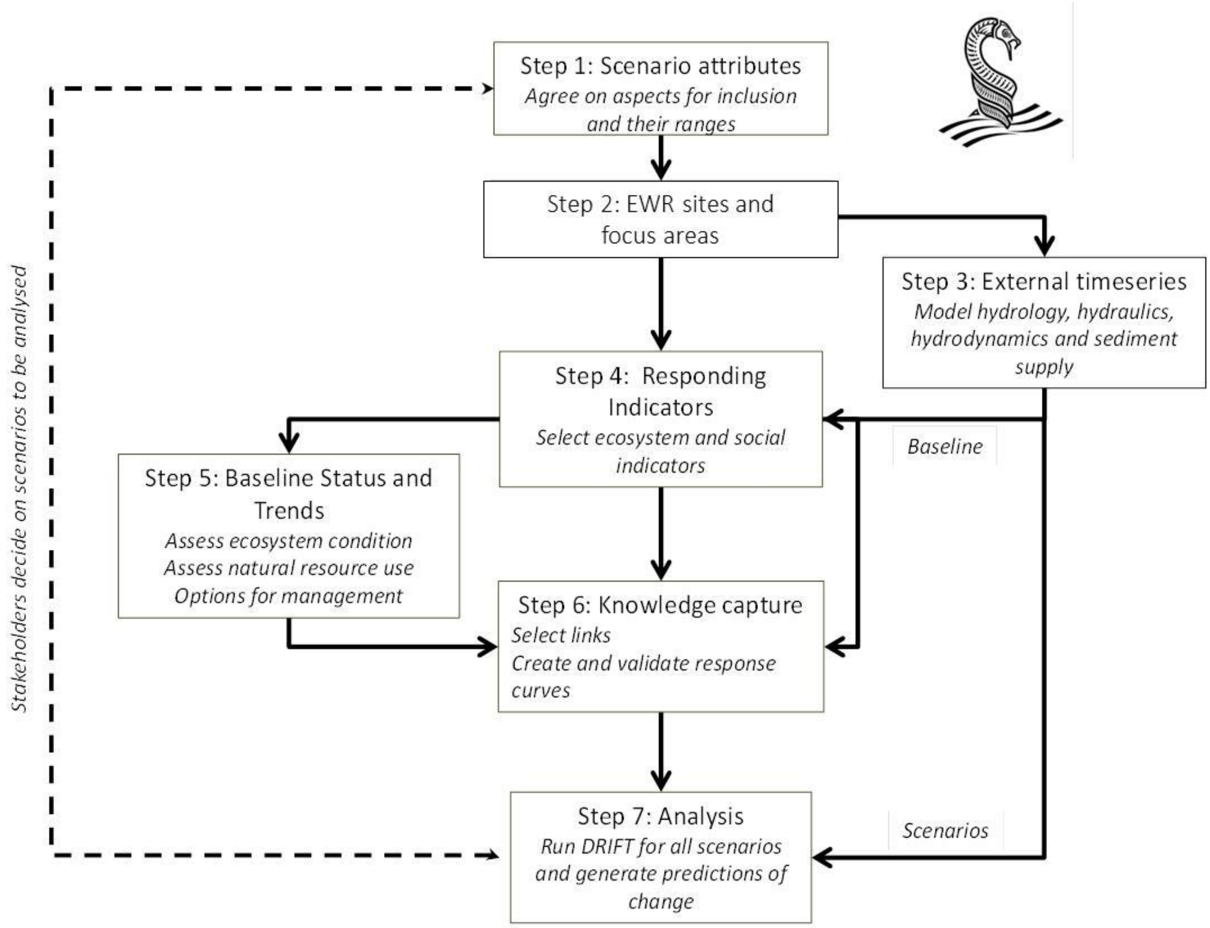

Figure 2-5: The seven-step DRIFT process

The Nylsvley Ramsar site is situated in the centre of the Nyl River floodplain **(Figure** 2-6), the upstream and downstream portions of the floodplain are excluded. However, the whole Nyl River floodplain was included in DRIFT-Nylsvley, which comprised three EWR zones of the Nyl River floodplain (**Section 5**).

The Makuleke Ramsar site is situated on the right bank of the Limpopo River (in South Africa) upstream of its confluence with the Luvuvhu River (**Figure** 2-7). Since the Limpopo River falls outside of the SoW (**Section 1.2**) the Area of Interest (AOI) for the DRIFT assessment was the Luvuvhu River floodplain situated in the southern part of the Makuleke Wetland complex, and thus the hydrodynamic modelling and DRIFT-Luvuvhu focussed on this area. However, it was necessary to consider the influence of water levels in the Limpopo River on the Luvuvhu River (**Section 6**). DRIFT-Luvuvhu comprised six EWR sites on the Luvuvhu River floodplain (**Section 6**).

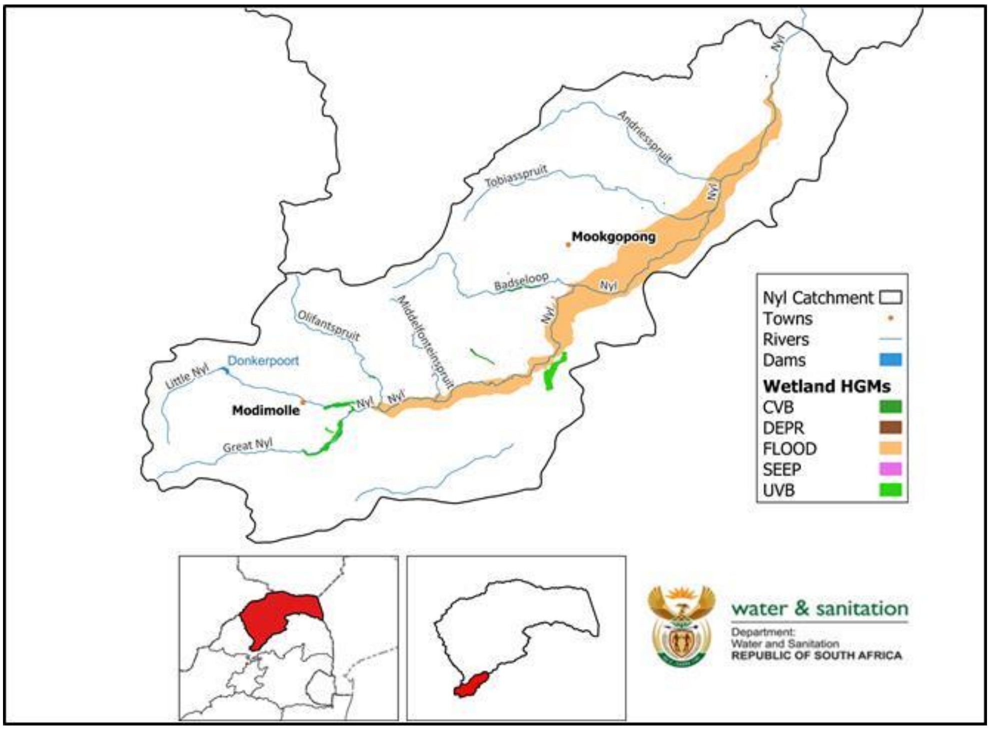

Figure 2-6: The Nyl River floodplain and tributaries (study area bottom left, Nyl River catchment bottom right). **CVB = channelled valley bottom, DEPR = depressional, FLOOD = floodplain, SEEP, UVB = unchannelled valley bottom; wetland**

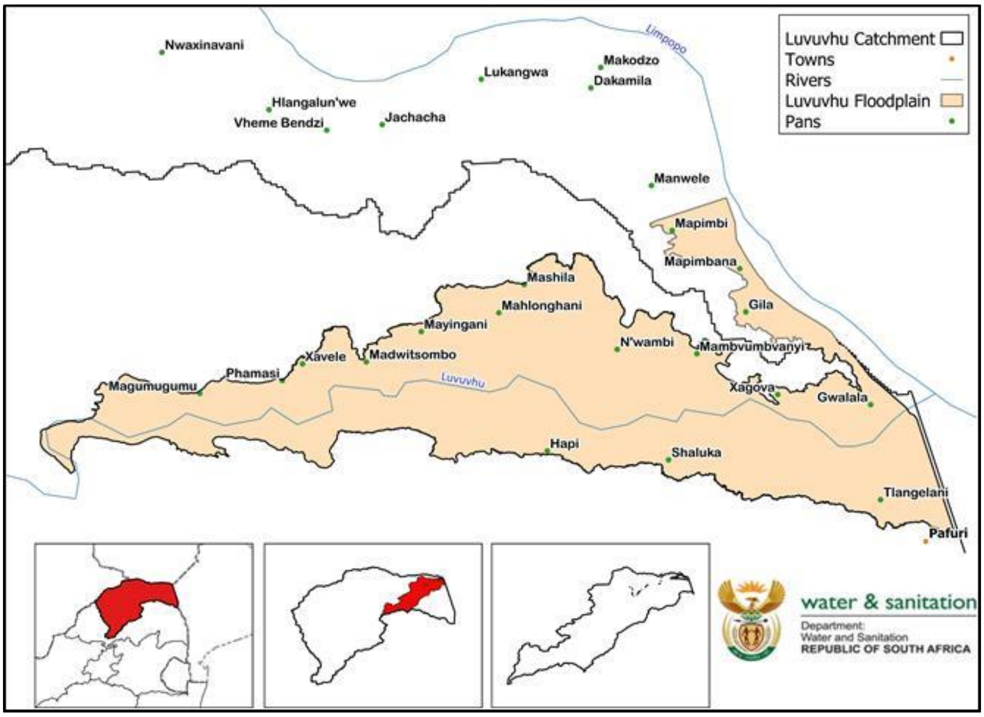

Figure 2-7: The Luvuvhu River floodplain and pans of the Makuleke wetland complex

2.5 Major assumptions and limitations

Predicting the effect of changes in flow, sediment and human pressures on rivers/floodplain wetlands is difficult because the actual trajectory and magnitude of the change is dependent on so many other variables, such as climate, politics, road networks, economics, and regulations. Thus, several assumptions and limitations apply to DRIFT:

- The modelled time-series of flow and other drivers of ecosystem condition approximate the actual conditions in the river/floodplain wetland over the period of record, and for the development levels selected. Should this not be the case, then the PES for the scenarios would be different to that used and so the scenario predictions, which are relative to this PES, could also change. For instance, if the PES hydrological time-series was changed, then the scenario predictions would change.
- Capturing the complexity of the system is confounded by the paucity of data. This is a universal problem, as by their nature human interactions with ecosystems are complex; complete certainty of the present and possible future characteristics of the ecosystems is not realistic. Instead, it is essential to proceed cautiously, and aid decision-making using best available information. The alternative is that development and management decisions are made without consideration of the consequences for the supporting ecosystems, eventually making management of sustainability impossible. Data paucity was addressed in DRIFT by accessing as much available knowledge as possible within the constraints of the Terms of Reference (ToR) using general scientific understanding; international scientific literature; local wisdom and insights from people who have worked in the rivers/floodplain wetlands of the region. This information was captured in a structured process that is transparent, with the inputs and outputs checked at every step. The response curves (and the reasoning used to construct them) are available for scrutiny within DRIFT. They can (and should) be updated as new information becomes available and new insights gained.

These inherent uncertainties mean that attention should be directed toward trends in the sequence of scenarios and the position of scenarios relative to each other, rather than towards absolute values.

3 VEGETATION MAPPING

3.1 Vegetation mapping and classification

As part of developing wetland-scale hydrodynamic models, it is necessary to link depth of inundation to the underlying landcover and distribution of vegetation types, which requires mapping or classification (Birkhead *et al*., 2022). The vegetation of both floodplains was assessed on two separate field trips and the data were classified into vegetation types, lifeforms and dominant species. These vegetation types were then compared with, and matched to, land cover classes (SANLC 2020) that were classified and mapped remotely from aerial imagery portraying a range of spectral bands from satellite data, mostly Sentinel 2 (described in more detail in **Section 4**).

3.1.1 Nyl River floodplain

The Nyl River floodplain was visited from 16 to 20 January 2023, during which time more than 300 hand-held points were surveyed (**Figure** 3-1**)**. At each position, the landcover was described (grassland, shrubland, bare earth and so on), lifeform noted, and the main species identified so that plant communities could be distinguished from one another. These data were used to guide the classification of different spectral bands into meaningful vegetation types (**Table** 3.1). The following vegetation types were identified using a combination of ground-truthing in combination with visual assessments of the distribution of types from high-resolution Near Colour Composites (NCC, Bing and Google Earth) and medium-resolution NCC and False Colour Composites (Sentinel 2A) imagery:

- emergent vegetation (reeds)
- floodplain grasses (central)
- floodplain grasses (edge)
- shrubs and trees
- trees.

Table 3.1: Landcover/vegetation types mapped for the Nyl River floodplain

Landcover/vegetation type	Representative species
Water	Aquatic vegetation (*Nymphaea lotus, Ceratophyllum demersum*)
Emergent vegetation	Reeds (*Phragmites australis, Cyperus fastigiatus)*
Floodplain grass (central)	*Oryza longistaminata*
Floodplain grass (edge)	*Leersia hexandra, Paspalum scrobiculatum, Panicum shinzii*
Shrubs/trees	*Searsia pyroides, Diospyros lycioides*
Trees	*Vachellia karroo, Ziziphus mucronata, Terminalia sericea*
Bare/sodic	None

The vegetation types (**Figure** 3-2) were incorporated spatially into the hydrodynamic model. Each vegetation type was assigned a preferred depth range based on life history traits (from the literature) and the hydrodynamic model generated time-series of the area, depth and duration of the depth ranges for each vegetation type (**Table** 3.2). These outputs were used as the primary driving variables in DRIFT and a range of hydrodynamic indicators were generated in DRIFT (minimum, maximum, average, median; for each season). The hydrodynamic indicators are given in **Table** 5.1.

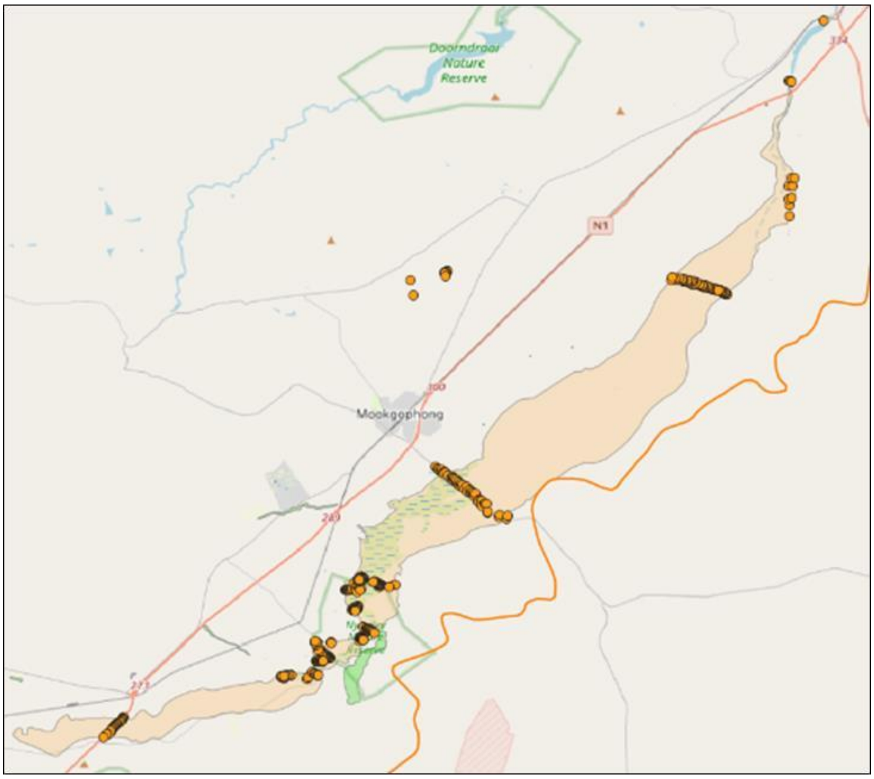

Figure 3-1: Waypoints where vegetation data were collected on the Nyl River floodplain

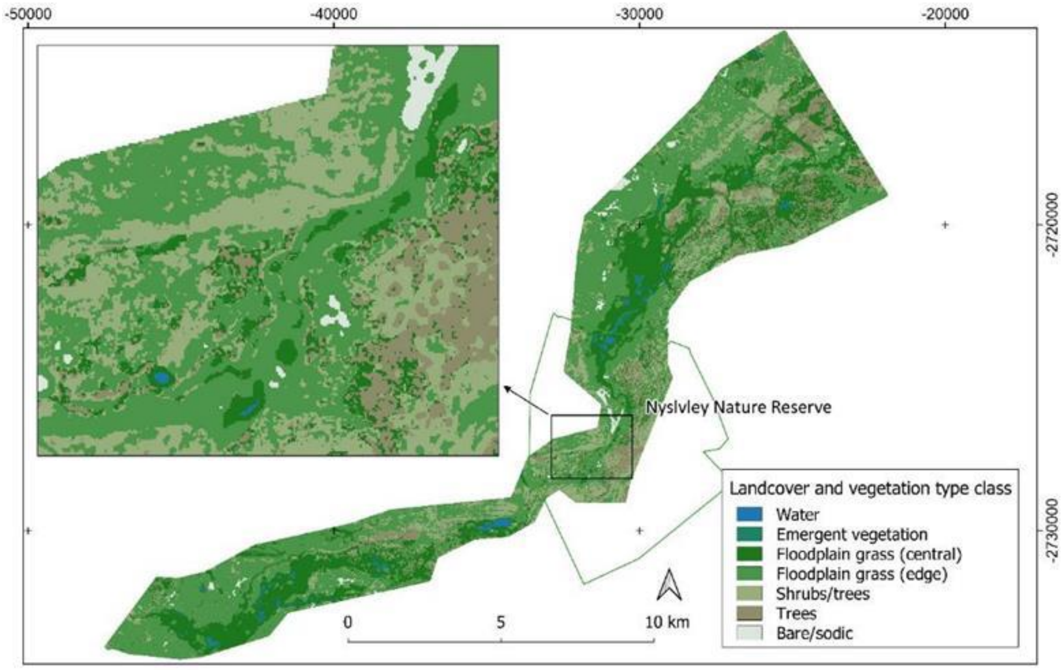

Figure 3-2: Landcover and vegetation types of the Nyl River floodplain derived from Sentinel 2 10-m spatial resolution multispectral imagery (3 September 2022); CRS is Hartebeeshoek94 Lo29

Table 3.2: Water-depth ranges for the landcover/vegetation types of the Nyl River floodplain

Landcover/vegetation type	Water depth (m)	Description
Water	≥ 0.50	Water depths of 0.5 m or more favours survival and persistence of aquatic vegetation (www.plantzafrica.com).
Emergent vegetation	0.10 – 0.30	Optimal depth to promote reed growth and vigour [Denny (1985), Ellery *et al*. (1995), Fraser and Keddy (2005), Gaudet (1992), Petr (2000), Sutcliffe (1974), Whigham *et al*. (1993)]
Central floodplain grass	0.10 – 0.50	The optimum depth range for *Oryza longistaminata* (central floodplain grass indicator) is 0.1 to 0.5 m. Depths > 0.75 m mean more energy must be spent to grow tillers that reach the water surface, at the expense of replenishing rhizomes. A long duration at depths of 0.25 is favourable [Marneweck (2023 pers. com.), Ellery *et al*. (2003), Gaudet (1992), Keddy (2005), McCarthy *et al*. (1986)].
Edge floodplain grass	0.05 – 0.30	Edge floodplain grasses commence growth with a small amount of inundation and grow and reproduce best at shallow depths < 0.3 m for extended periods [Gaudet (1992), Keddy (2005)].
Shrubs and trees	≤ 0.10	A lack of inundation to deeper depth will encourage woody species to encroach into the grassy floodplain areas. Any persistent inundation, even shallow facilitates non-woody dominance of the floodplain by excluding woody species recruitment.

3.1.2 Luvuvhu floodplain

The Luvuvhu floodplain was visited from 16 to 22 Oct 2022; during this time 25 pans and ~600 waypoints were surveyed (**Figure** 3-3).

Figure 3-3: Waypoints on Luvuvhu River floodplain (black outline) where vegetation data were collected

The same process as used for the Nyl was used to classify (**Table** 3.3) and map the vegetation (**Figure** 3-4). The models for the Nyl and Luvuvhu River floodplains differ from each other because the two ecosystems are functionally quite different. The Nyl River has a narrow floodplain of grassland and backwaters that are regularly flooded by the small Nyl River. The focus of the assessment was on the Nyl floodplain, and the hydrodynamic model was developed to provide information inundation depths on the floodplain linked to discharge in the Nyl River.

The Luvuvhu floodplain is a much larger, and more arid floodplain system with pans that are intermittently filled by a combination of flooding from the Luvuvhu and Limpopo rivers, localised runoff and direct rainfall. Understanding these interactions was imperative for the assessment and so a hydrodynamic model was developed with hydrological data for the rivers with water balances computed for the pans. The two modelling processes are described in **section 4.1** for the Nyl floodplain and **section 4.2** for the Luvuvhu floodplain.

Table 3.3: Landcover/vegetation types mapped on the Luvuvhu River floodplain

Indicator	Description		
Tree	Vegetation	Floodplain	Woodland
Tree/sedge/shrub			Mix of trees/shrubs/sedge plants
Shrub/grass			Scrub thicket
Shrub/grass/bare			Mix of shrubs/grass plants and bare ground
Grass/bare			Mix of grass/sedge plants and bare ground
Tree		Riparian	Forest/thicket
Bare/riverbed			Reeds/potential reed habitat
Bare	Landcover	Bare	No plants
Water		Water	Aquatic plants, refuge areas

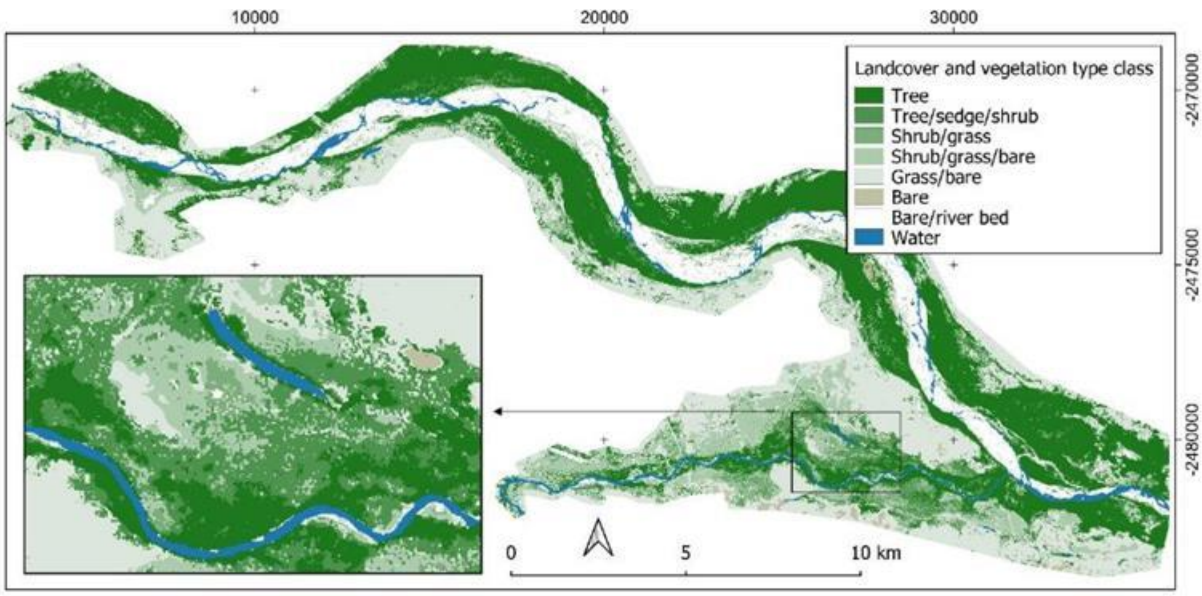

Figure 3-4: Landcover and vegetation types mapped at Luvuvhu floodplain, derived from 10-m spatial resolution multispectral imagery (23 September 2022). Inset shows the Luvuvhu River and Nwambi Pan; CRS is Hartebeeshoek94 Lo31

4 HYDRODYNAMIC MODELLING

4.1 The Nyl River floodplain

4.1.1 Background and existing studies

The Nyl River floodplain is a unique and highly-biologically productive ecological system. It is a large ecosystem that supports a variety of wildlife, several Red Data bird species and is recognised internationally as an important wetland habitat. Nylsvley, situated in the centre of the floodplain, was designated a Ramsar site in 1998 and covers an area of 3 970 ha[2].

The Mogalakwena River Basin Study, completed in 1992, investigated the behaviour of the floodplain at Nylsvley. However, since no calibration data were available, the hydrological models used at the time, Water Resources of South African 1990 (WRSM90) and Dam Break (DAMBRK), were unable to satisfactorily simulate flows across the floodplain, determine how it is flooded or what volumes of water are required for the different vegetation zones. The 1992 study therefore recommended that further investigations be undertaken (DWAF 2004a).

In 1996, the (then) Department of Water Affairs and Forestry (DWAF) commissioned a study to model the hydrology and hydraulics of the Nyl River floodplain to complement other ongoing biological and ecological work. The original 5-year study (1997 to 2001) recognised the need to allow an adequate time frame to collect hydraulics data - these being essential for model calibration and verification. The study was extended to 2003 due to a delay in the topographical survey (using Light Detection And Ranging, viz. LiDAR; **Section 4.1.2.1**) which was undertaken in 2001 after the floods of 2000 (DWAF 2004a).

The main purpose of the Nylsvley 2003[3] project was the development of computational models for simulating the hydrological and hydraulic behaviour of the Nyl River Floodplain that were used to determine ecological impacts associated with potentially altered flow regimes. The hydrological modelling component was undertaken by Stewart Scott International and is described in DWAF (2004a). The hydraulic component was carried out by the Centre for Water in the Environment (at Wits University) and is described in DWAF (2004b). Three companion papers describing the studies were published in Water SA, *viz*. (1) Havenga *et al.* 2007 (Part 1: Hydrological modelling); (2) Birkhead *et al.* 2007 (Part 2: Modelling hydraulic behaviour); and (3) Kleynhans *et al.* 2007 (Part 3: Ecological impacts of upstream water-resource development scenarios).

The hydraulic model developed in the 2003 study was the basis for the eco-hydrodynamic modelling in this study. For brevity, a general description of the 2003 hydraulic model is provided in Section 4.1.2, but for further detail consult the aforementioned DWAF reports and Water SA companion publications.

4.1.2 2003 hydraulic modelling study

4.1.2.1 Study area and model structure

The study area extends from the N1 National Road (at Middelfontein) to the Mookgophong-Roedtan Road (Route 519) at Mosdene (**Figure** 4.1) and was selected to include the most ecologically-important

[2] https://rsis.Ramsar.org/ris/952

[3] The study was completed in 2003 and is referred to as such, although publications cited are dated later.

areas of the floodplain, such as the Ramsar site. Other practical considerations taken into account included the proximity of hydraulic model boundaries to streamflow gauges; suitable locations for flow gauging in a difficult monitoring environment; the lateral extent of the floodplain; the frequency and extent of flooding; the distribution of wetland plant communities, and available resources for topographical surveys.

For modelling purposes, the study area was divided into three distinct, contiguous zones, defined by four road crossings and the locations of water level monitoring locations. For each of these an individually calibrated and verified hydraulic model was developed:

- Reach 1: Middelfontein to District Road D924 (~upstream boundary of Nylsvley);
- Reach 2: D924 to D925 (Vogelfontein - downstream boundary of Nylsvley); and
- Reach 3: D925 to Regional Road R519 (Mosdene).

Each reach is represented as an EWR zone in DRIFT-Nylsvley (see **section 5.2**):

- Reach 1 = EWR zone 15_Nylsvley1
- Reach 2 = EWR zone 16_Nylsvley2
- Reach 3 = EWR zone 17_Nylsvley3.

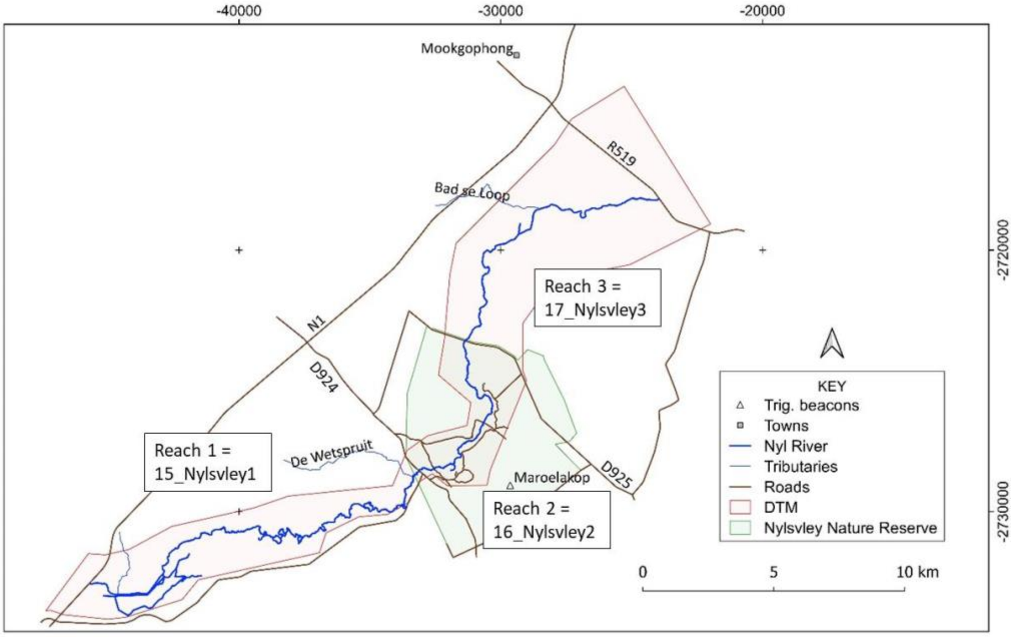

Figure 4.1: Location of the three reaches (2003) and EWR zones (PES 2022) on the Nyl River Floodplain in DRIFT-Nylsvley[4]; CRS (Coordinate Reference System) is Hartebeeshoek94 Lo29

4.1.2.2 Data collection

The following data were collected from 1996 and 2000 for the development, calibration and verification of the models:

---

[4] The Digital Terrain Model (DTM) extends slightly upstream and downstream of the floodplain.

- topographical and photographic surveys
- observed water levels and discharges
- observed rainfall records
- measurements of evaporation and infiltration.

The Nyl River floodplain is extremely flat, so ground elevations need to be defined to a high degree of accuracy for meaningful predictions of the flow depth and water volume required to inundate the floodplain. The floodplain was mapped using airborne LiDAR and photographed digitally. Laser mapping rapidly generates high-density, geo-referenced digital elevation data with accuracies comparable to land surveys but is significantly faster than traditional airborne surveys. Airborne laser mapping systems can determine ground surface topography through vegetated cover, which is particularly useful in areas of low relief, such as the Nyl River floodplain. The absolute accuracy of the elevation data is 150 mm and relative accuracy can be less than 50 mm (Birkhead *et al.* 2007). The de-archived LiDAR data from the 2003 study are in ASCII text file format: a 100 mm filter (for thinning the data sets) was applied to Nylsvley (Reach 2), whereas Reaches 1 and 3 were thinned with a 200 mm filter (i.e. slightly coarser resolution). In addition to the LiDAR, a digital imaging camera was used to produce geo-referenced ortho-photographs.

The locations of nine water-level monitoring locations used in the study are illustrated in **Figure** 4.2: four are/were[5] DWS stations (A6H0xx), while eight gauge plates (GPx) were installed prior to the 2003 study, mostly in Nylsvley. The latter were monitored periodically (~5-day intervals) providing ~300 readings from January 1996 to June 2001, and were the main source of water levels used to develop the hydraulic model. Historic water level data were available from the DWAF hydrological database for stations A6H002 (Deelkraal) and A6H013[6] (Mosdene), but were not used for model development due to changes in gauge datums. Also, no corresponding discharge measurements were available. As part of the 2003 study, DWAF upgraded the existing monitoring network (at Deelkraal, Vogelfontein and Mosdene) and installed a new station at Middelfontein (A6H039). Prior to the 2003 study, the relative elevations of gauges were unknown. Thus, to make use of monitored water levels, the elevations of all gauge plates were surveyed relative to the same elevation datum used for topographical mapping.[7]

No floodplain discharge measurements existed prior to the 2003 study, and flow was therefore measured at key locations (bridge crossings) during the project to develop rating or ‘stage-discharge’ relationships. The highest gauged inflow at Middelfontein was 15.7 m^3/s in April 2000, and an outflow of 35.3 m^3/s was recorded at Mosdene in February 2000.

Local rainfall contributes to the water balance of the floodplain, and two rainfall stations are in close proximity to the study area. The Nylsvley Station (0590307) was used to estimate the volume of rain falling on the inundated floodplain. Calculation of this volume required estimation of the inundated area, which was obtained from empirical relationships developed between inflow and flooded area for each of the three reaches. Losses due to evapotranspiration, infiltration and ponded storage after flooding were also accounted for. Average monthly evaporation rates were used in the study, which were

[5] The current status of the stations is unknown, with database records extending variably to 2021/22

[6] prior to A6H038, which was installed in 1997 but vandalised within a year

[7] Ostensibly the South African Land Levelling Datum (SA LLD), but this was not explicitly determined from the DWAF/LiDAR surveys nor documented in the 2003 study.

obtained using actual evaporation measurements on the floodplain and application of the energy balance method. Water balances for each of the reaches were determined to quantify the relative contributions of inflows and outflows, and to develop empirical relationships for the losses arising from infiltration and ponding that are difficult to measure.

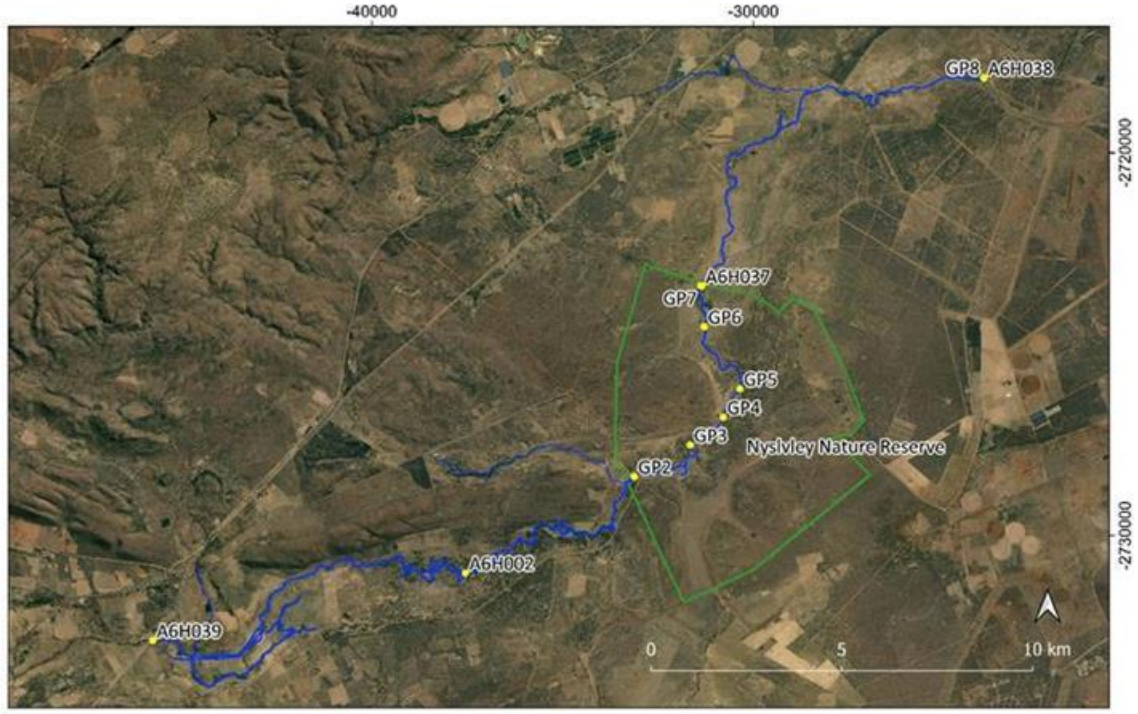

Figure 4.2: Water level and discharge monitoring locations along the Nyl River (GP = Gauge Plate; A6H0xx = DWS Stations); CRS is Hartebeeskhoek94 Lo29

4.1.2.3 Hydraulic model development and application

Flooding behaviour was analysed one-dimensionally (1-d), and a suite of four modelling tools was used: QuickSurf, RiverCAD, HECRAS and HEC DSSVue. QuickSurf is a surface modelling system (based on FelixCAD) that converts surface mapping data (e.g. LiDAR point data) into contours, grids and triangulated irregular networks. LiDAR does not penetrate water surfaces and thus the depth of the river channel was not defined by the survey, and therefore a low flow channel was superimposed on the Digital Terrain Model (DTM). RiverCAD is an advanced graphical modelling environment used in the US Army Corps of Engineers' 1-d unsteady flow analysis software, HECRAS (Hydrological Engineering Centre River Analysis System). RiverCAD provided the tools necessary for positioning and extracting cross-sections and other relevant data required for HECRAS hydraulic modelling.

Resistance coefficients for the Nyl River and floodplain (Manning's *n*) were adjusted using the unsteady flow calibration. Boundary conditions were in the form of upstream discharge hydrographs and downstream (measured) rating relationships. Tributary inflows and rainfall contributions were specified as daily discharge timeseries. Modelling instabilities prevented the use of discharge timeseries to account for losses, and these were incorporated using the pump extraction facility and efficiency relationships developed by correlating daily losses with water levels.

The wettest season in the six-year record (1999/2000) was used for model calibration, and the remaining data was used for verification. Modelled and measured stage fluctuations compared well at all monitoring locations, with simulated behaviour generally within 100 mm of observed values. The application of the floodplain model was from 1973 to 2001 using discharge hydrographs derived from hydrometric stations[8] for the Nyl River and its tributaries.

4.1.3 Eco-hydrodynamic modelling (this study)

4.1.3.1 Topographical data: processing 2001 LiDAR survey

The LiDAR data from the 2001 survey (ASCII format; **Section 4.1.2.2**) was processed for use in Geographic Information Systems (GIS) software. The plan (x-y) co-ordinates of the survey were found to be in the (projected) Hartebeeshoek94 Lo29 datum, but the de-archived data needed to be corrected for false northing and sign conventions; this was necessary for correct geo-referencing. The survey data were processed as follows:

- the disparity between co-ordinate formats in ASCII text files were corrected (to the Hartebeeshoek94 Lo29 datum), merged for the study area and imported to GIS
- a Triangulated Irregular Network (TIN) was created from point data
- a DTM was developed from the TIN using 5-m grids
- contours were digitised at 0.2-m intervals from the DTM.

The DTM and superimposed 0.2-m interval contours are illustrated in **Figure** 4.3 for a section of the study area at Nylsvley. The contouring was used to assist with delineation of the wetland, which is described in Volume 1 (DWS 2024).

4.1.3.2 Data collection

From a hydrodynamic modelling perspective, no additional survey data were planned to be collected along the Nyl River floodplain. Opportunity was taken after the survey of the Luvuvhu floodplain (in October 2022; **Section 4.2.3.1**), however, to also survey a cross-section at Nylsvley between GP3 and 4 (**Figure** 4.2) using a Trimble® Catalyst™ GNSS9 receiver with decimetre accuracy10. This provided an accurately measured profile across the floodplain (since the eco-hydrodynamic modelling is based on 2001 LiDAR data), which is linked to the spatial distribution of species and lifeforms between the treelines on the left and right bank. It also provided a useful comparison with the topography from the 2001 LiDAR survey (**Figure** 4.4**)**. Overall, the profiles compare well - although as expected, the LiDAR topography does not indicate the full channel depth which is likely due to pooled water and/or thick aquatic vegetation.[11] The species composition of the wetland vegetation was assessed by the wetland specialist at all the surveyed waypoints in January 2023 (Volume 1, DWS 2024). The objectives of the wetland assessment were to determine the Present Ecological State (PES); collect data to ground-truth

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[8] infilled and extrapolated from the upstream hydrometric stations to the edge of the floodplain

[9] Global Navigation Satellite System

[10] https://geospatial.trimble.com/products-and-solutions/trimble-catalyst

[11] An ellipsoid-LLD offset of -19.72 m was used (based on the GNSS and LiDAR surveys) which compares well with a value of -19.81 m from the SAGeod2010 (Chandler and Merry 2010); this confirms that the LLD was used in the 2003 study.

the wetland delineation; and to relate plant species distributions and landcover to the satellite imagery processed to map and classify landcover (described in **Section 4.1.3.5**).

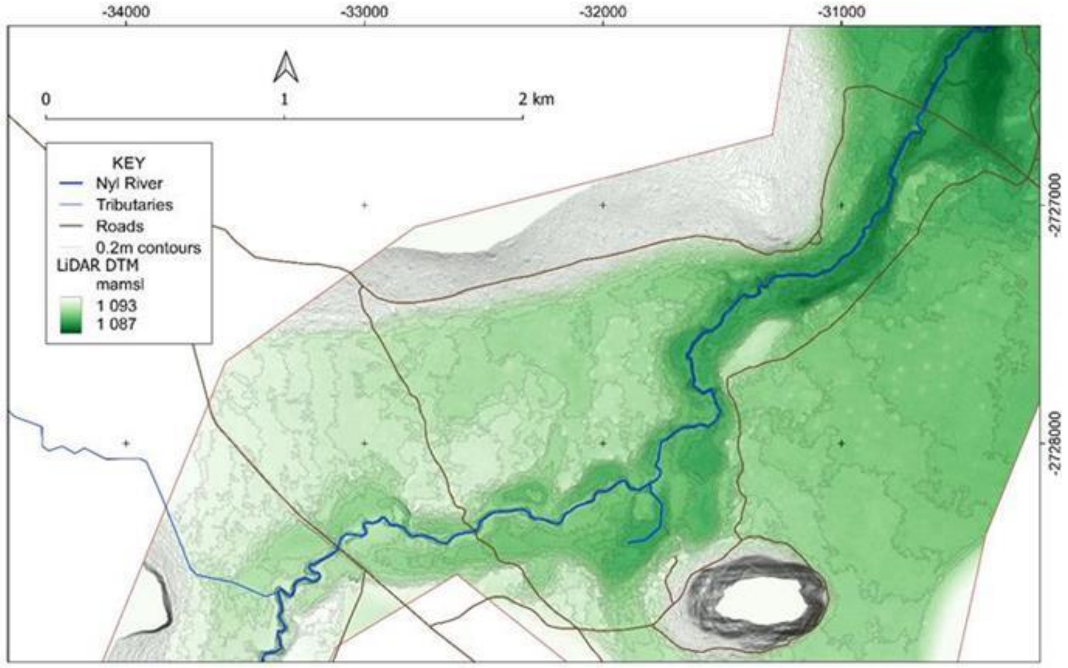

Figure 4.3: DTM and superimposed 0.2 m contours at Nylsvley; CRS is Hartebeeshoek94 Lo29

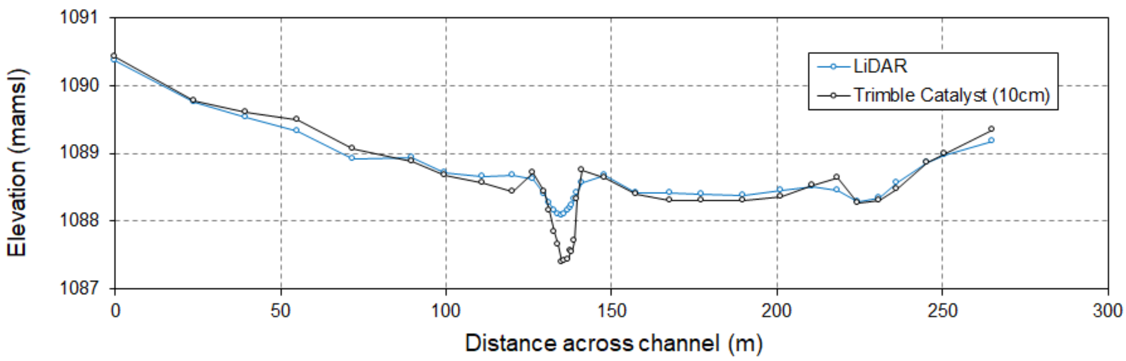

Figure 4.4: Cross-section derived from 2001 LiDAR data and the cross-section surveyed with a Trimble® Catalyst™ GNSS receiver (October 2022)

4.1.3.3 HECRAS Nyl River Floodplain Model

The pre-processing software used in the 2003 study (*viz*. QuickSurf and RiverCAD) was not required, because GIS and bespoke software were used to pre-process the topographical data and post-process standard hydraulic results (Birkhead *et al.* 2018; 2022). The 2003 model setup files (CAD and HECRAS) were de-archived and the drawing files reformatted from FelixCAD[12] to GIS shape file format (**Figure** 4.5); HECRAS enables read-continuity with ongoing version updates and the software is in the public domain. Geometric (topographical) data in the 2003 HECRAS model, which were derived from RiverCAD, are unfortunately not georeferenced.[13] To produce a more meaningful model setup for this study, and to assist with post-processing results for use in DRIFT-Nylsvley, the HECRAS geometric file was completely re-setup for this project. This required aligning the georeferenced cross-section plan data points (x-y) with HECRAS chainage-elevation data (chainage-z) to produce the requisite x-y-z triordinates.

Figure 4.5: 141 de-archived, reformatted and georeferenced cross-sections on the Nyl River floodplain, on a Bing satellite image; CRS is Hartebeeshoek94 Lo29

The intention was to combine the three 2001 HECRAS sub-models for reaches 1 to 3 into a single setup with accompanying inputs and outputs (**Figure** 4.6**)**. This was not instituted, however, since firstly HECRAS cannot accommodate internal stage-discharge boundary conditions between adjacent models, and secondly, daily rainfall fluxes are based on modelled inflows to each reach (refer to **Section 4.1.3.4**). Therefore, the three-submodel structure was retained in this application.

The (re-setup) HECRAS floodplain model was parameterised using data from the 2003 'application', including bank stations and resistance values (Manning's *n*); reach lengths; ineffective flow areas; downstream boundary conditions (ratings); and losses (pump extractions). To validate the model setup (i.e. to confirm that results from this study are consistent with previous simulations), the models for

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[12] FelixCAD uses a *.flx file format and it is not widely supported anymore - the current standard CAD file format is *.dwg.

[13] The geometric file contained only coordinates of chainage (distance across channel) and elevation.

Reaches 1 to 3 were run with timeseries data from the 2003 model application, *viz*.: 1973 to 2001 daily discharge for the Nyl River, tributaries and rainfall contributions.

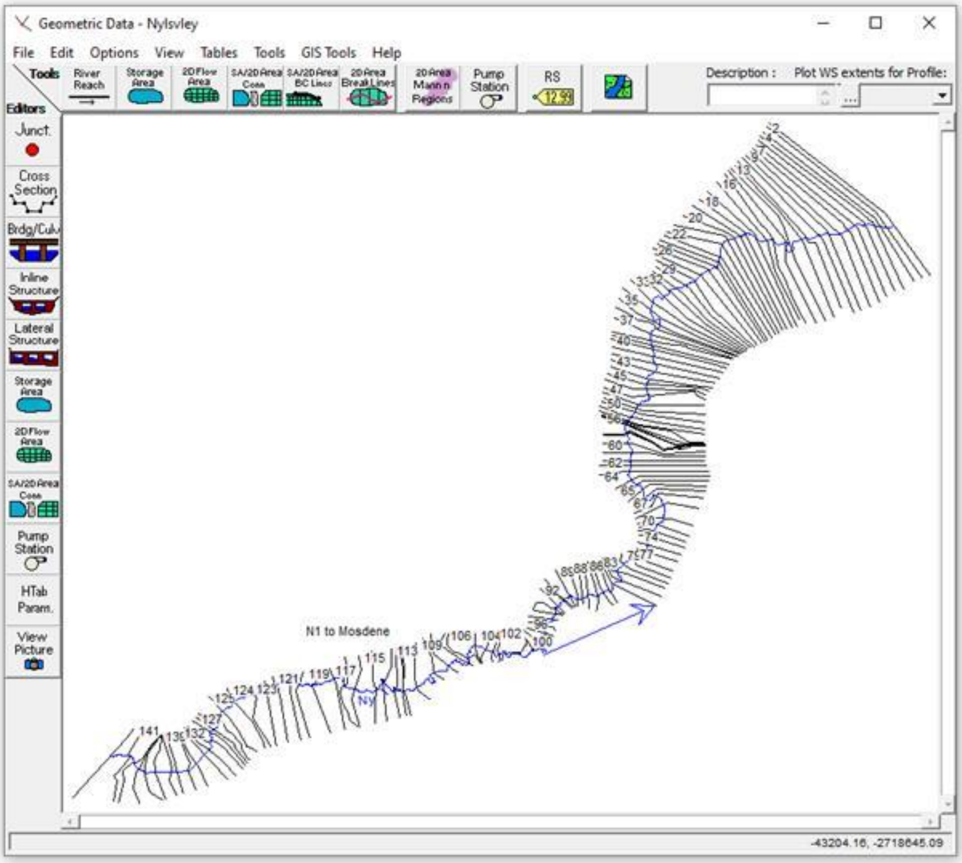

Figure 4.6: Plots of georeferenced geometric data in HECRAS

4.1.3.4 Hydrological timeseries data

The hydrological modelling for the rivers component of this study (River Assessment (Volume 2): Data Collection and Analysis Report) was extended for the rivers that flow into the Nyl River for which no modelled daily flows were available for use in the hydrodynamic model and in DRIFT-Nylsvley. This involved disaggregation of modelled monthly volumes to daily discharges for the Naturalised and PES flow scenarios from 1925 to 2021. Daily discharge timeseries were produced for the Groot Nyl, Klein Nyl and Olifantspruit Rivers, which cumulatively yield the flow in the Nyl River as it flows into the floodplain at the upstream end; northern tributaries, *viz*. Middelfonteinspruit, De Wetspuit and Bad sê Loop; and the Blindefontein (southern tributary). Mean Annual Runoff (MAR) volumes are given in **Table** 4.1**.**

Table 4.1: Modelled MAR for the rivers flowing into the Nyl River across the floodplain

River / tributary	MAR (1925 to 2021) ($10^6 m^3$)	
	Naturalised	PES
Nyl at N1 Road	37.18	31.94
Middelfonteinspruit	6.63	6.23
De Wetspruit	0.33	0.23
Bad sê Loop	0.47	0.33
Blindefontein	1.38	0.98

The daily rainfall records from the '2003' study were from the Nylsvley Station (0590307) and extended to 2001. The Climate Hazards Group and InfraRed Precipitation with Station (CHIRPS) data were procured for the period 1981[14] to 2021 and were used to extend station-based measurements. Monthly rainfall depths for these two data sources (*viz.* Station 0590307 and CHIRPS) were compared for the period 1981 to 2021 with no substantial bias. The estimated Mean Annual Precipitation (MAP) for the period 1925 to 2021 is 601 mm.[15] Daily timeseries of rainfall fluxes require estimates of inundated areas for each of the three reaches, which were correlated with modelled Nyl River flows as follows (Birkhead *et al.* 2007):

<u>Reach 1</u>

$A = 0.0033Q^3 – 0.14631Q^2 + 2.316Q – 0.2165 \quad 0 < Q < 16$

$A = 12.9 \quad Q \geq 16$ Equation 4.1

<u>Reach 2</u>

$A = 2.513Q^{0.564} – 0.684 \quad 0 < Q < 20.1$

$A = 13.2 \quad Q \geq 20.1$ Equation 4.2

<u>Reach 3</u>

$A = 28.459Q^{0.204} – 17.792$ Equation 4.3

where A is the surface area of inundated floodplain (km^2) and Q is the Nyl River inflow (m^3/s)

4.1.3.5 Mapping landcover and vegetation distributions along the Nyl River floodplain

To make the 'standard' output of hydraulic analyses more relevant for use in a hydro-ecological model such as DRIFT, it is necessary to link depth of inundation to landcover and vegetation type, which requires mapping or classification (Birkhead *et al.* 2022).

To map landcover and vegetation distributions along the Nyl River floodplain, two public domain medium-resolution (10 - 30 m/pixel) satellite platforms were considered, *viz*.: Landsat and Sentinel. The European Space Agency's Sentinel data and NASA's Landsat data are widely used sources of Earth observations that provide historical information spanning almost half a century (Landsat); a range of spectral bands; and spatial resolutions of down to 10 m/pixel (Sentinel). The Landsat earth observation mission is the longest continuous running system of satellites for optical remote sensing, and dates to the launch of Landsat 1 in 1972. Landsat 8, the most recent Landsat satellite (launched in November

14 dataset commences 1981
15 range 286 to 861 mm

2013), has nine spectral bands in the visible to Short Wave Infrared (SWIR) spectral range and spatial resolution of down to 30 m/pixel (15 m/pixel for the panchromatic[16]).

The Sentinel mission dates back to 2014 (Sentinel 1), with the first Sentinel 2 satellite launched a year later. The mission is a constellation with twin satellites: Sentinel 2A and 2B (launched on June 2015 and March 2017, respectively). Sentinel 2 data has spectral bands very similar to Landsat 8, but higher spatial resolution for its visible and Near InfraRed (NIR) bands. A comparison of Sentinel 2 and Landsat 8 spectral bands and spatial resolutions are provided in **Table** 4.2 and **Figure** 4.7.

Table 4.2: Sentinel and Landsat spectral bands and spatial resolutions

Sentinel 2					Landsat 8[17]			
Band	Description	Spatial resolution (m/pixel)	Central wavelength (nm)[18]	Band width (nm)	Band	Description	Spatial resolution (m/pixel)	Wavelength (nm)
1	Coastal aerosol	60	442.3	20	1	Coastal aerosol	30	430-450
2	Blue	10	492.1	65	2	Blue	30	450-510
3	Green		559.0	35	3	Green	30	530-590
4	Red		665.0	30	4	Red	30	640-670
5	Vegetation red edge	20	703.8	15				
6			739.1	15				
7			779.7	20				
8	NIR1	10	833.0	115	5	NIR	30	850-880
8A	NIR2	20	864.0	20				
9	Water vapour	60	943.2	20				
10	SWIR cirrus		1376.9	30	9	SWIR cirrus	30	1360-1380
11	SWIR1	20	1610.4	90	6	SWIR1	30	1570-1650
12	SWIR2		2185.7	180	7	SWIR2	30	2110-2290

16 All visible colours of the spectrum

17 https://www.usgs.gov/ (accessed 30/06/21)

18 nanometres

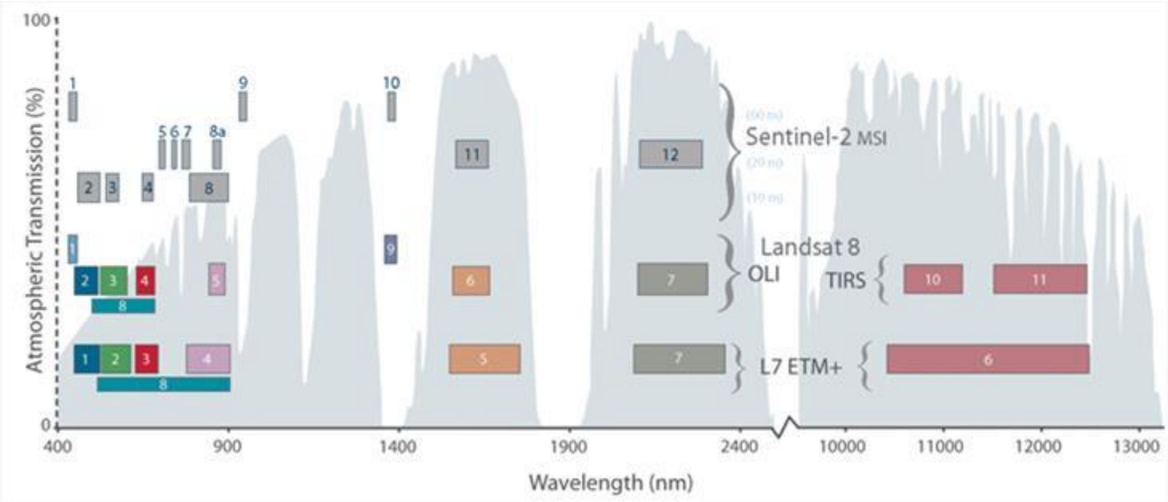

Figure 4.7: Spectral bands: Landsat 7, 8 and Sentinel 2

Given the higher spatial resolutions of the Sentinel 2 imagery, combined with the vegetation red-edge, this platform was selected for detailed mapping of landcover, vegetation distribution and classification of vegetation types. The mapping is based on cloud-free imagery towards the end of the 2022 dry season (3 September 2022). The seasonal timing is important to differentiate between semi-permanent[19] and seasonal wetlands. Towards the end of the dry season, surface water is confined to ponded areas and the scenes are generally cloud-free. The floodplain falls within a single Sentinel 2A scene, and the Level-2A (L-2A) product composed of ~110 x 110 km tiles or granules in the UTM/WGS84[20] projected Coordinate Reference System (CRS) was downloaded through the Copernicus open Access Hub[21]. The L-2A product provides atmospherically corrected[22] surface reflectances. **Figure** 4.8 shows a Natural Colour Composite (NCC) and False Colour Composite (FCC) of the study area.

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[19] which depends on the extent of the previous season's inundation (inflows and rainfall)

[20] Universal Transverse Mercator/World Geodetic System

[21] https://scihub.copernicus.eu

[22] The atmospheric correction of Sentinel 2 images includes the correction of the scattering of air molecules, the absorbing and scattering effects of atmospheric gases, and the correction of absorption and scattering due to aerosol particles.

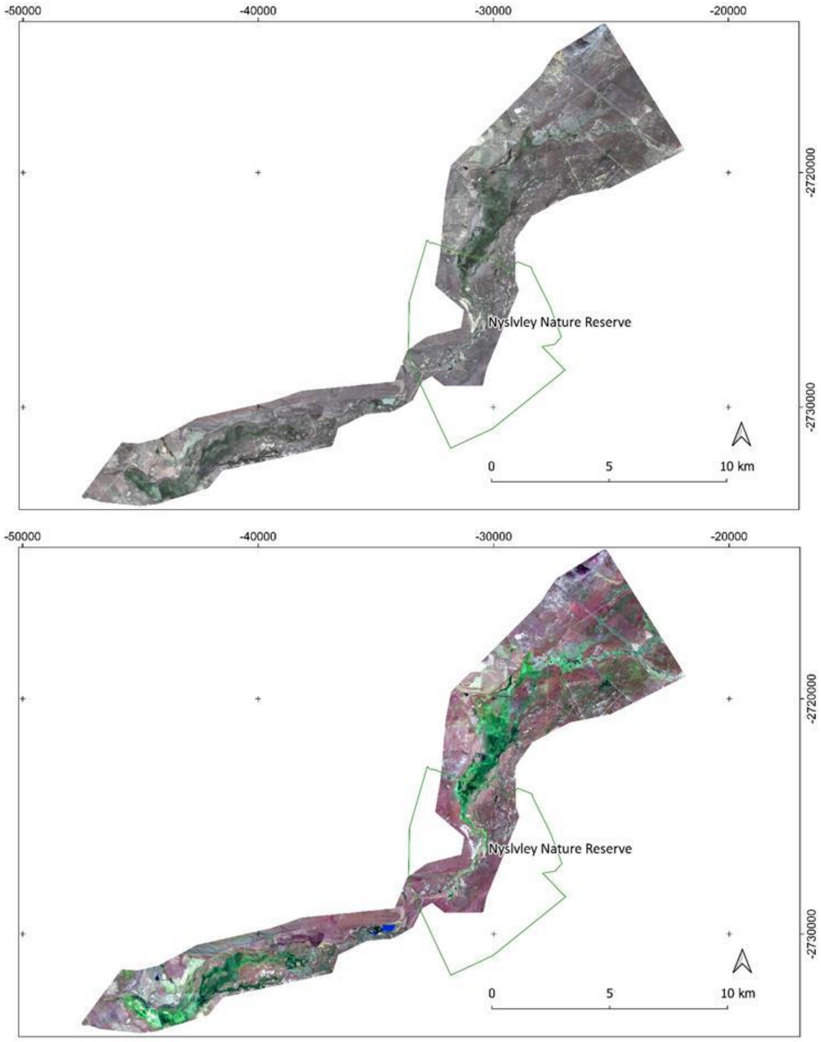

Figure 4.8: Natural Colour Composite (top; Red Green Blue (RGB) = Bands 4, 3, 2) and False Colour Composite (bottom; RGB = Bands 11, 8, 4) of the study area, derived from Sentinel 2 10 m/pixel[23] spatial resolution imagery from 3 September 2022; CRS is Hartebeeskhoek94 Lo29

Various methods were investigated for categorising the different landcover and vegetation types along the Nyl River floodplain from the 2022 imagery (**Figure** 4.8), including:

- supervised classification (Maximum Likelihood, Spectral Angle Mapping, Mahalanobis and Minimum Distances; Parallelepiped and Binary Encoding)
- unsupervised classification (k-means and ISODATA)
- object-based image segmentation
- thresholding indices computed using different spectral bands, including:
  - vegetation indices:
    - Normalised Ratio Vegetation Index (NRVI)
    - Difference Vegetation Index (DVI)
    - Normalised Difference Vegetation Index (NDVI)
    - Enhanced Vegetation Index (EVI)

[23] Excluding SWIR1(Band 11) at 20 m/pixel resolution (refer to Table 4.2) which was resampled to 10 m/pixel

    - Corrected Transformed Vegetation Index (CTVI)
    - Soil Adjusted Vegetation Index (SAVI)
    - Transformed Soil Adjusted Vegetation Index (TSAVI)
  - Modified Normalised Difference Water Index (MNDWI)
  - Normalised Burn Ratio (NBR)
  - Tasseled Cap Transformation (TCP).

None of these classification methods was found to be adequate on its own, mainly because of the varied and complex mosaic of landcovers and vegetation types on the floodplain.

Therefore, a stepwise approach was used for mapping, as follows:

1 Open water surfaces were extracted from the combination of the NIR Band (Band 8) and the MNWDI with threshold values of < 0.23 and < 0.55, respectively. The MNWDI is given by Equation 4.4 (Xu 2005, cited by Szabó *et al.* 2016).

$$\frac{SWIR1 - Green}{SWIR1 + Green}$$

Equation 4.4

where *SWIR*1 is shortwave infrared Band 11, and *Green* is Band 3

2 The second of the short-wave bands, i.e. SWIR2 (Band 12), was used to extract water mixed with vegetation (or emergent vegetation) and bare or sodic landcovers (i.e. with no or minimal plant cover) using minimum and maximum threshold values of 0.15 and 0.40, respectively.

3 The suitability of the vegetation indices listed previously (e.g. NDVI, EVI) for classifying the remaining vegetation types was assessed. They were, however, all inadequate for distinguishing between different types of vegetation of similar health or stress condition (*viz*, grasslands, shrubs and trees). To classify the remaining types, unsupervised classification[24] was used based on the Red, NIR and SWIR1 bands. The following four broad vegetation classes were thus identified using a combination of ground-truthing (**Section 4.1.3.2**) and visual assessments of the distribution of vegetation types from high-resolution NCCs (Bing and Google Earth) and medium-resolution NCC and FCC (Sentinel 2A) imagery[25]:

- central floodplain grasses
- edge floodplain grasses
- shrubs and trees
- trees.

The mapping using Sentinel 2A imagery thus resulted in seven broad classes, and the rendered landcover classification for the Nyl River Floodplain is illustrated in **Figure** 4.9.

[24] k-means with Hill-Climbing (Rubin 1967)

[25] This was carried out with substantial input from the wetland vegetation specialist.

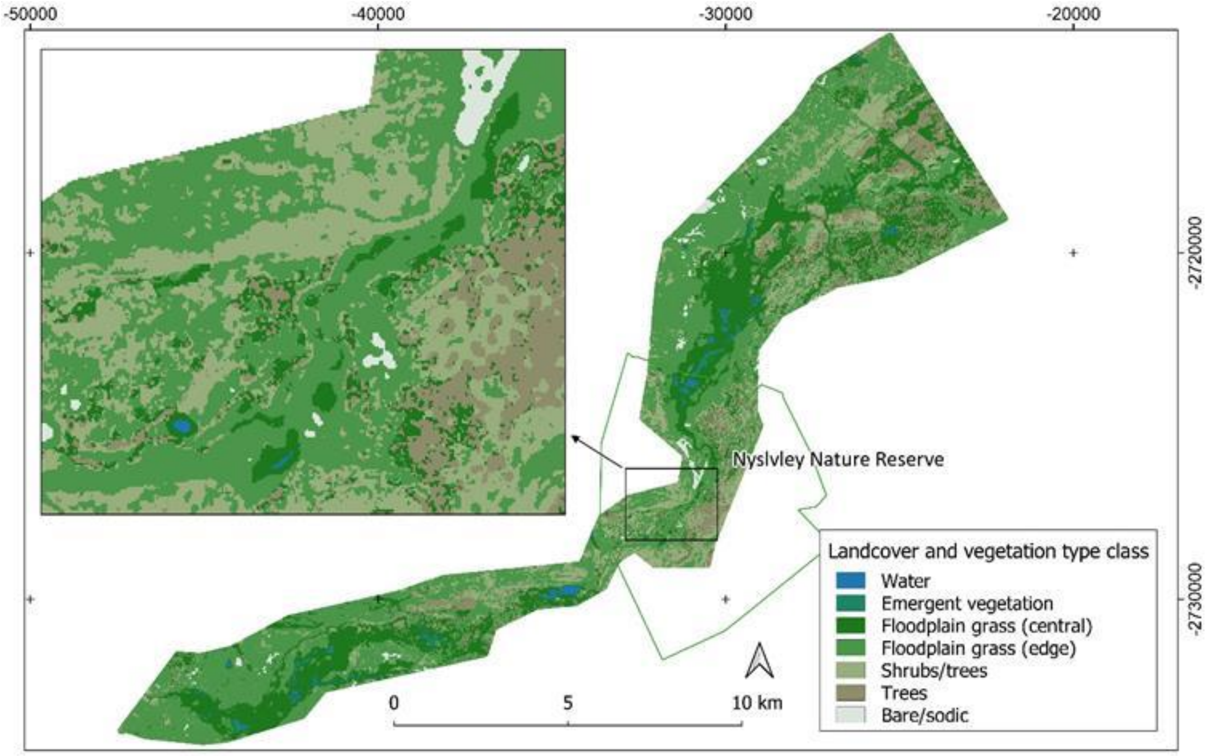

Figure 4.9: Classified landcover and vegetation types for the Nyl River floodplain, derived from Sentinel 2 multispectral imagery (10 m/pixel spatial resolution) taken 3 September 2022; CRS is Hartebeeshoek94 Lo29

4.1.3.6 Post-processing hydrodynamic modelling results for use in DRIFT

As discussed previously, the 'standard' results from the hydrodynamic model need to be post-processed to give ecological relevance to the hydraulic and hydrological indicators used in DRIFT-Nylsvley. Bespoke software was developed for post-processing, and is similar to that used in studies of other floodplains and wetlands in South Africa, Malawi and Zambia (Birkhead and Brown 2021; Birkhead *et al.* 2018; 2022). The computational methodology involved:

- digitally delineating the floodplain area represented by each of the cross-sections (and assigning a cross-section id)
- deriving a points data file on a 10 m x 10 m grid with the following attributes: reach id; representative cross-section id; landcover/vegetation type (refer to **Section 4.1.3.5**); and bed elevation (assigned from the LiDAR DEM; **Section 4.1.3.1**)
- writing HECRAS (cross-section) stage timeseries results to a data file for each reach
- using bespoke software to read the above data files and compute timeseries per reach and land cover/vegetation type of:
  - average and maximum depth
  - inundated area per depth range (**Table** 4.3)
  - total inundated area.

Depth ranges are defined based on geomorphological and/or ecological criteria, e.g. studies have shown that wild rice grows best in depths of 100 to 500 mm (Marneweck 1998) and were derived from the observed 2022 PES (**Figure** 4.9) and summary statistics calculated that represent appropriate prevailing hydromorphological conditions (area, depths and durations of inundation) across the floodplain. Derivation of the depth class ranges is described in **section 3.1.1**.

Table 4.3: Depth class ranges applied to classified landcover and vegetation types

Landcover/vegetation type		Depth range (m)
#	Description	
1	Water	≥ 0.50
2	Emergent vegetation	0.10 – 0.30
3	Central floodplain grass	0.10 – 0.50
4	Edge floodplain grass	0.05 – 0.30
5	Shrubs/trees	≤ 0.10

Hydraulic modelling and post-processing of results was carried out for both Naturalised and PES scenarios. Timeseries plots of inundated area and average depth for the PES scenario are illustrated in **Figure** 4.10.

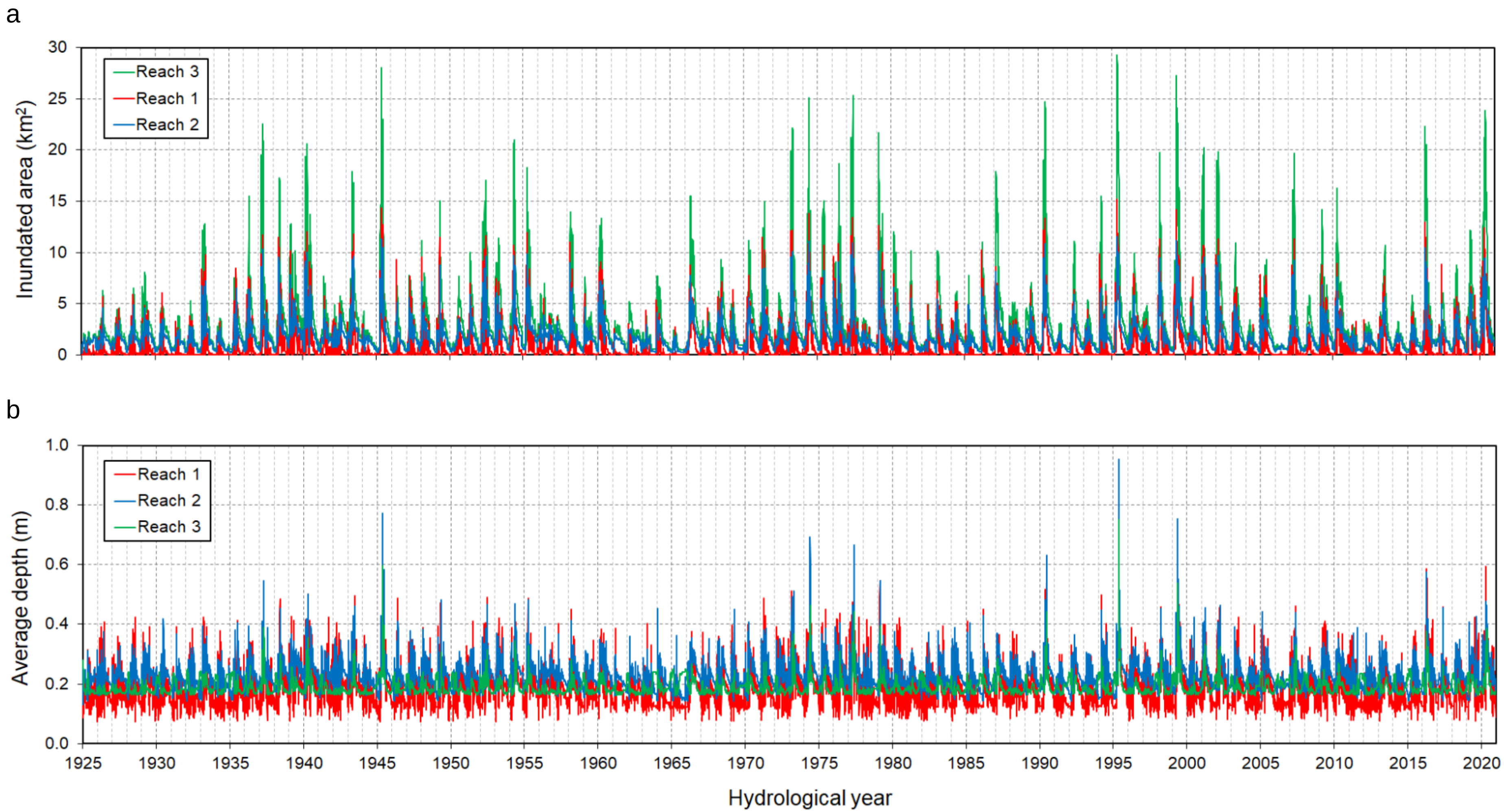

Figure 4.10: Modelled PES scenarios (1925 to 2021) for the Nyl River floodplain: a) inundated area, b) average depth

4.2 The Luvuvhu River floodplain

4.2.1 Background

The Makuleke wetland complex was designated a Ramsar site in 2007 (yellow boundary in **Figure** 4.11), most of which lies in the Kruger National Park (KNP), bordered by Zimbabwe and Mozambique to the north and east respectively. Prominent features include riverine forests, riparian floodplain forests, floodplain grasslands, river channels and pans[26]. The pans are paleo-channel features of relative low topography (i.e. depressions) in the floodplain, which are intermittently filled by a combination of flooding from the Luvuvhu and Limpopo Rivers, localised runoff and direct rainfall. They are important in this ecosystem as they retain water in the dry season and provide habitat for wildlife and waterbirds throughout the year. There are ~30 pans associated with the Luvuvhu and Limpopo Rivers in South Africa (**Table** 4.4).

Table 4.4: Pans on the Luvuvhu and Limpopo River floodplains in South Africa

Luvuvhu	Limpopo southern floodplain
southern floodplain (right bank)	Banyini
Hapi [a,b]	Xipokonyola
Shaluka [b]	Shisasi
Tlangelani [a,b]	Makwadzi [a,b]
northern floodplain (left bank)	Hulukulu
Phamasi [b]	Nwaxinavani
Magumugumu [b]	Hlangalun'we [a,b]
Xavele [b]	Jachacha [a,b]
Madwitsombo [a,b]	Vheme Bendzi [a,b]
Mayingani	Lukangwa
Mahlonghani [a,b]	Makodzo
Mashila [b]	Dakamila
Nwambi [a,b]	Manwele
Mambvumbvanyi [b]	Mapimbi
	Mapimbana [a,b]
	Gila [b]
Luvuvhu/Limpopo (near confluence)	
Xagova [b]	
Gwalana [b]	

[a] water was present in October 2022; [b] hydraulic features were surveyed in (bed/water level/control)

4.2.2 Available information and data collation

Two main types of information are necessary to develop a hydraulic model for the Luvuvhu River floodplain, viz. topographical and hydraulic data.

[26] https://rsis.Ramsar.org/ris/1687

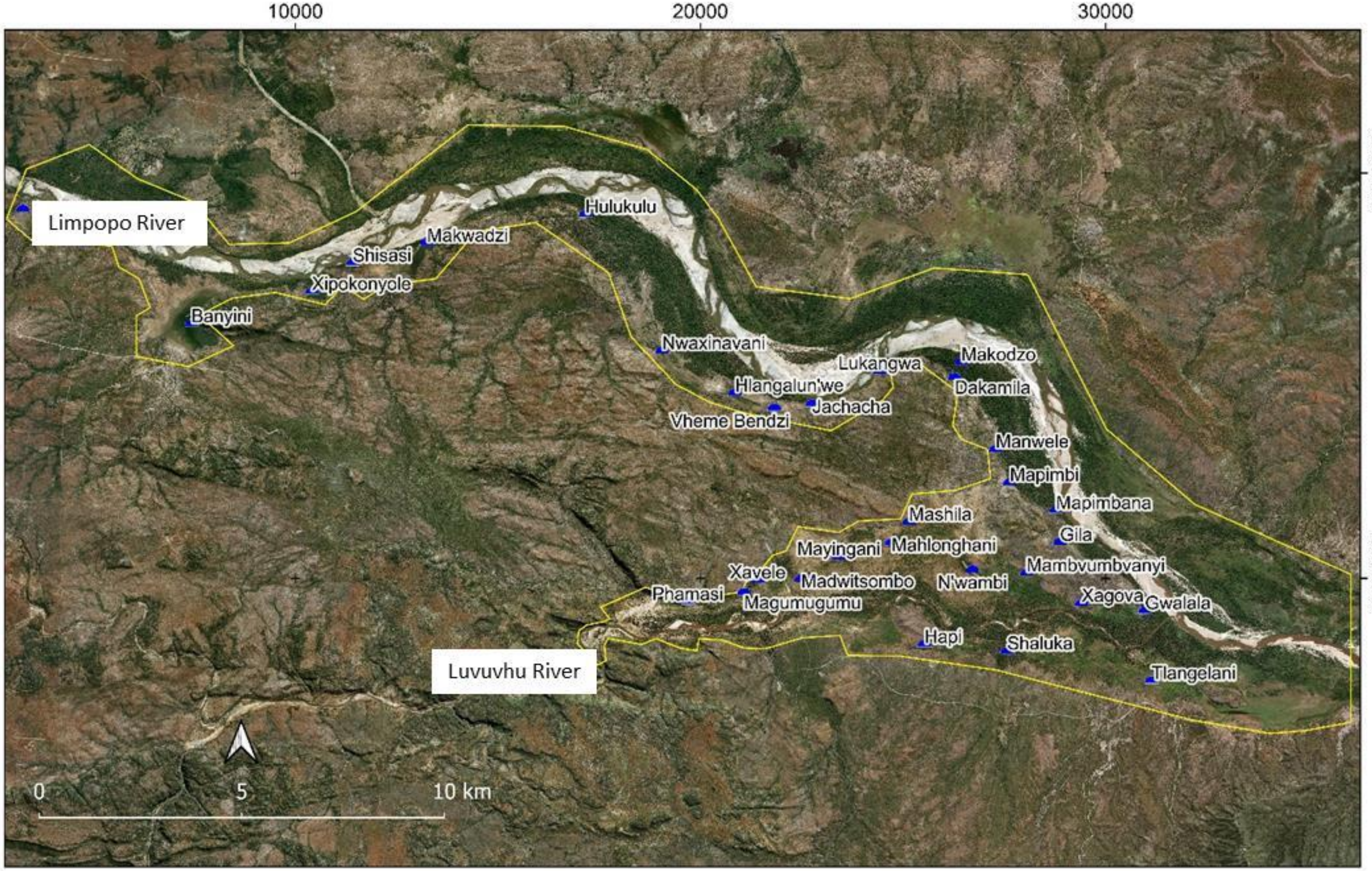

Figure 4.11: Pans in South Africa on the Luvuvhu (south) and Limpopo (north) floodplains in the Makuleke wetland complex (yellow boundary); CRS is Hartebeeshoek94 Lo31

4.2.2.1 Topography: Digital Terrain Model

Topographic information is required in the form of a Digital Terrain Model (DTM). Two global public domain 30 m resolution Digital Elevation Models (DEMs)[27] sources were investigated: the Shuttle Remote Topography Mission (SRTM) and Advanced Land Observing Satellite (ALOS), as well as the national DEM from the National Geo-spatial Information (NGI) Centre[28]. The national DEM was used in the hydraulic study of the Pongola River Floodplain (Birkhead *et al.* 2018), but unfortunately its vertical accuracy is inadequate for this use in this study. The ALOS AW3D30 provides the best accuracy of the available public domain resources, but the topographical relief is too coarse for hydraulic modelling. By request of the DWS, a LiDAR survey for the Makuleke wetland complex was investigated but was beyond the scope of this project so a cost-effective medium-accuracy DTM was sought.

This was found in GeoSmart's 2 m resolution Level 3 DEMSA2 DTM, with a quoted vertical accuracy of 0.5 m[29]. The DTM was extracted from stereo aerial imagery (dated 2008 and 2015), with > 95% of surface features taller than 1.5 m removed from the DEM (**Figure** 4.12). Contours at 0.2 m intervals were generated from the DTM to assist with the delineation of the floodplain (Volume 1, DWS 2023).

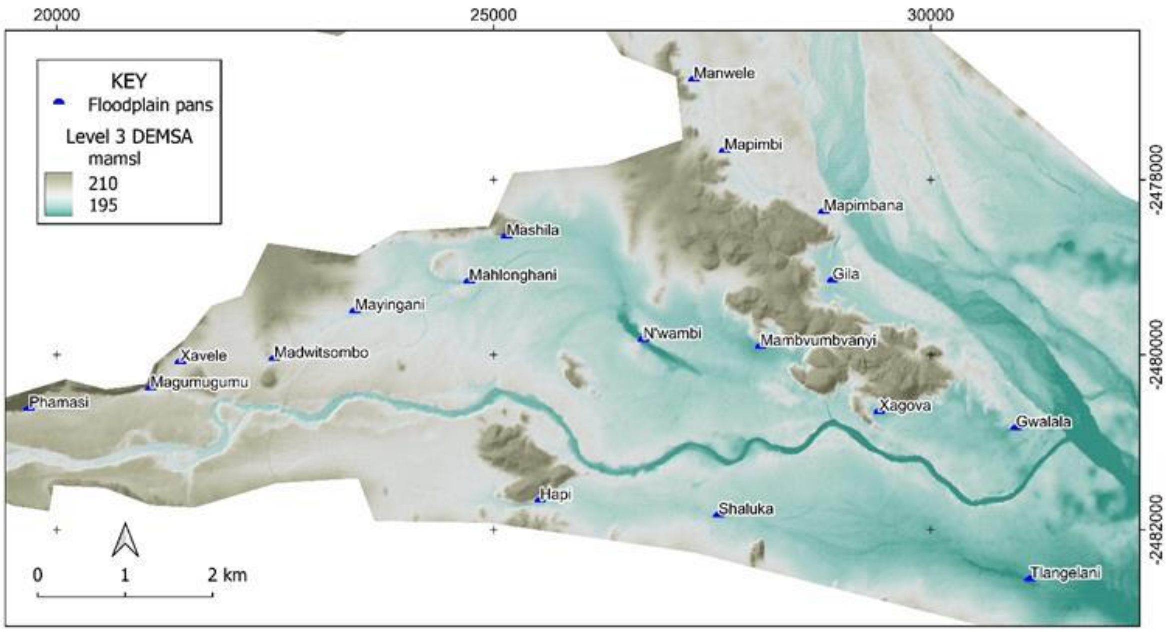

Figure 4.12: Digital Elevation Model of the Luvuvhu River floodplain to the Limpopo River confluence (~0.5 km east of the Gwalala Pan) from the 2 m resolution Level 3 DEMSA2 DTM; CRS is Hartebeeshoek94 Lo31

The point elevation data[30] that was surveyed using a Trimble® Catalyst™ DA2 receiver on the data collection field trips (**Section 4.2.3.1**) provided comparative measurements to assess the vertical

[27] A DTM provides the height of the ground surface (terrain), whereas a DEM does not necessarily provide the height of the terrain (i.e. may include structures, vegetation, etc.) and thus the generic term 'elevation' applies
[28] a component of the South African Department of Agriculture, Land Reform and Rural Development
[29] https://geosmart.space/products/demsa2.html
[30] 335 spot measurements with a vertical accuracy within 0.11 m

accuracy of the DTM, which was within 0.5 m for 73%, and to within 1.0 m for 91%, of the points surveyed.

4.2.2.2 Hydraulic information

Hydraulic information includes discharge (flow) and water level (stage) data. The discharge records available for the Luvuvhu, Mutale and Limpopo Rivers are:

- DWS Station A9H012 on the Luvuvhu River (Mahinga), ~60 km upstream of the confluence with the Mutale River, rated[31] to 367 m^3/s
- DWS Station A9H013 on the Mutale River (in the Kruger National Park), ~2 km upstream of the confluence with the Luvuvhu River, rated to 135 m^3/s
- DWS Station A7H004/8 on the Limpopo River (Beit Bridge), ~155 km upstream of the confluence with the Luvuvhu River, rated to 9 375 m^3/s.

While records from DWS Stations A9H012 and A9H013 are valuable for modelling low-to-medium and high flows in the lower Luvuvhu River (in the KNP), extreme high flows are required for the river to breach its banks and spill onto its floodplain, which are relatively infrequent. Hydraulic modelling (**Section 4.2.5**) indicates that flows in the range ~750 to 1 000 m^3/s are required to breach the river banks and attendant levees in the upper section of the floodplain, and initiate widespread flooding. These discharges exceed the rated flows of the gauges upstream. Thus, the hydrodynamic model depends heavily on sparse hydraulic data and the results of modelled hydrological behaviour (refer to **Sections 4.2.5** and **4.2.6.2**, respectively).

The only available water level[32] records for the Luvuvhu River in the AOI are from Pafuri Bridge (DWS Station A9H032; **Figure** 4.13), with records from October 2017.[33]

Figure 4.13: DWS Station A9H032 on the Luvuvhu River at Pafuri Bridge - left: 21 October 2022; right: 24 February 2023, ~89 m^3/s

[31] maximum discharge that the station can infer from water levels measurements

[32] local gauge stage datum - i.e. not SA LLD

[33] supplied by Vernon Green (Control Auxiliary Services Officer; DWS Hydrology, Limpopo region)

Historic flood levels for the Luvuvhu floodplain are available from two sources (**Figure** 4.14**)**:

- at beacons constructed along the tarred road crossing the Luvuvhu River (right and left floodplain) that mark the flood level of the February 2000 flood
- marked on the wall of the Theba Pump House near the confluence of the Luvuvhu and Limpopo Rivers for the years 1958, 1972, 1975, 1981, 1988, 1996, 2000 and 2013 (i.e. nine years in the last 65 years = ~1/7.2 years <u>on average</u>); the largest marked flood was in 2000 followed by 2013 (**Figure** 4.15).

a

b

c

Figure 4.14: Marked historic floods levels: a) (February 2000) - on beacons on the tar road crossing the Luvuvhu River, b) marked on a wall at the Theba Pump House between 1958 and 2000[34] - date unknown, c) includes the 2013 flood that is the second highest recorded after 2000 (photograph October 2022)

[34] supplied by Sandra Visagie (previous section ranger at Pafuri, KNP)

Figure 4.15: 2013 floods: a) damage to the Wilderness Safari Lodge (left bank of the Luvuvhu River ~1 km downstream of Pafuri Bridge)[35]; b) 20 January 2013 flooding across the northern side of the road crossing the Luvuvhu River (flow from right to left)

The floodplain experienced its most recent flood in 2013, photographs of which were used to obtain approximate levels (**Figure** 4.15**)**.

[35] "Floods in KNP January 2013" - presentation by Sandra Visagie

Unfortunately, there are no stage-level records for any pans in the Makuleke wetland complex. Available data are limited to:

- spot maximum depth measurements and estimates of storage (%) taken during fish surveys between 1993 and 1996[36]
- the state (dry or pooled) of 23 pans over a three-year period from December 2016 to 2019 (Turner and Riddell 2020).

4.2.3 Data collection

The available data described in **Section 4.2.2.2** were insufficient and/or in the wrong format[37] for developing a hydrodynamic model of the Luvuvhu River floodplain, and so additional data were collected on two field trips in October 2022 and February 2023.[38]

4.2.3.1 Field trip: October 2022

The data collection trip to the floodplain was done at the end of the 2022 dry season[39] (17 to 21 October 2022). The purpose of the trip was to:

- collect topographic and hydraulic information (described in this report); and
- collect data for ground-truthing the delineation of the floodplain, as well as for relating vegetation types (species and growth forms) and landcover to processed satellite imagery to inform classification of vegetation types (**Section 4.2.4**)
- assess the PES (described in the Wetland Assessment Volume 1 – Ecostatus and Priority Wetlands.).

Given the short-duration of data collection, large extent of the floodplain, and the need to visit as many pans as possible, survey techniques were used that facilitated rapid data collection whilst providing suitable accuracy (**Figure** 4.16). This included a:

- Trimble® Catalyst™ DA2 GNSS receiver with decimetre accuracy, linked to an android smartphone running QField[40] for positioning and data recording
- radio-controlled boat configured with a Lowrance HDS depth sounder with onboard data recording for bathymetric surveys in pans that are too shallow and/or not accessible with a boat due to safety considerations (*viz*. presence of hippopotami and crocodiles). This applied to the ‘less-temporary’ and deeper pans, namely Nwambi and Hapi on the Luvuvhu floodplain (**Figure** 4.20**b** and **Figure** 4.19**a**, respectively) and Makwadzi along the Limpopo River (**Figure** 4.21**c**).

---

[36] supplied by Dr Bennie van der Waal (Pan data 97.xls)
[37] e.g. elevation datums
[38] A field trip was also carried out during the dry season in August 2022, but was directed at the river sites, with a short reconnaissance visit to the Nwambi Pan
[39] during low flow conditions and to use roads that are generally closed under wet conditions
[40] QField is the professional mobile application for QGIS

The following survey data was collected:

- Luvuvhu River:
  - two cross-sectional profiles (e.g. **Figure** 4.17)
  - longitudinal water surface profile
  - elevations of levee breaches where the water level overtops banks and flows onto the floodplain
- floodplain pans:
  - if ponded, water surface elevation and depth
  - lowest bed level
  - full supply or 'invert' level
- elevations of levee breaches at pans adjacent to the Limpopo River
- flood levels marked on the Theba Pump House wall (**Figure** 4.14 and **Table** 4.5)
- spot elevations on the floodplain[41]
- elevation of the gauge datum at Station A9H032 on the Luvuvhu River at Pafuri Bridge (**Figure** 4.13)
- top-of-plinth elevation at Trigonometric Beacon 'GWALALI' (**Figure** 4.18).

Table 4.5: Surveyed levels on the Theba Pump House and on Pafuri Bridge (Figure 4.14 and Figure 4.15b)

Flood marker	Elevation (mamsl)
Theba Pump House	
09/02/2000	199.27
20/01/2013	199.00
09/02/1977	198.77
18/01/2000	198.72
27/01/1972	198.45
22/01/1958	197.23
04/02/1981	196.94
07/03/1977	196.81
22/02/1975	196.50
11/02/1996	196.45
28/02/1988	196.15
Pafuri Bridge	
25/02/2000	207.32
20/01/2013	206.51

Topographical elevations in the DTM (refer to **Section 4.2.2.1**) use the South African Land Levelling Datum (SA LLD). Thus, to compare 'ellipsoidal' elevations surveyed with the GNSS satellite receiver (**Figure** 4.16 left), it is necessary to obtain the LLD-ellipsoidal offset. Trigonometric Beacon 'GWALALI' is situated on the hill ~350 m NE of the Xagova Pan near the Luvuvhu-Limpopo Rivers confluence. A survey of this trigonometric beacon yielded an offset of -10.36 m relative to the ellipsoidal elevation. Comparatively, an offset of -10.13 m gives a zero median error from 335 spot measurements and those derived from the DTM (refer to Section 4.2.2.1); the SAGeoid2010 model's average offset for the study

[41] to compare with the DTM (refer to Section 4.2.2.1)

area is ~-10.00 m with an estimated standard deviation of 0.07 m (Chandler and Merry 2010). All ellipsoidal elevations surveyed were converted to the SA LLD, which is the DTMs datum as rendered in **Figure** 4.12.

Of the main 30 floodplain pans listed in **Table** 4.4, 23 were visited, including all the major pans on the Luvuvhu floodplain. Four pans on the Luvuvhu River floodplain had water, though only Nwambi and Hapi had depths > ~40 cm where hippopotami were present; five pans along the Limpopo River had water but all, except Makwadzi, were very shallow. Photographs of the pans accessed on the October data collection are shown in **Figure** 4.19 to **Figure** 4.22. The locations of GNSS spot elevation measurements are shown in **Figure** 4.23.

Figure 4.24 shows shrinkage and cracking of bed substrate in the Shaluka Pan, which was noted for most pans visited. This indicates high clay content; clay has a low hydraulic conductivity (or permeability), which reduces seepage interaction between surface (ponded) water in the pans and alluvial bank storage/groundwater in the floodplain.

4.2.3.2 Field trip: February 2023

Some additional data was collected on the high flow river trip in February 2023 when visiting the river site 14_Mutale2:

- stage level was recorded and discharge was measured at the Pafuri Bridge crossing over the Luvuvhu River using a Sontek Acoustic Doppler Profiler (89 m^3/s**; Figure** 4.16);
- water level changes since October 2022 were observed in the Nwambi, Hapi and Shakula Pans:
  - the level in the Nwambi Pan was similar
  - the level in the Hapi and Shaluka Pans was higher (the Shaluka Pan was dry in October 2022); since the Luvuvhu River had not breached its banks between field trips, the increase was due to localised runoff.

Figure 4.16: Survey equipment used for topographic and hydraulic data collection on the Luvuvhu River floodplain: left – surveying with a Trimble® Catalyst™ DA2 GNSS receiver; right – radio-controlled boat with onboard Lowrance HDS depth sounder on Nwambi Pan

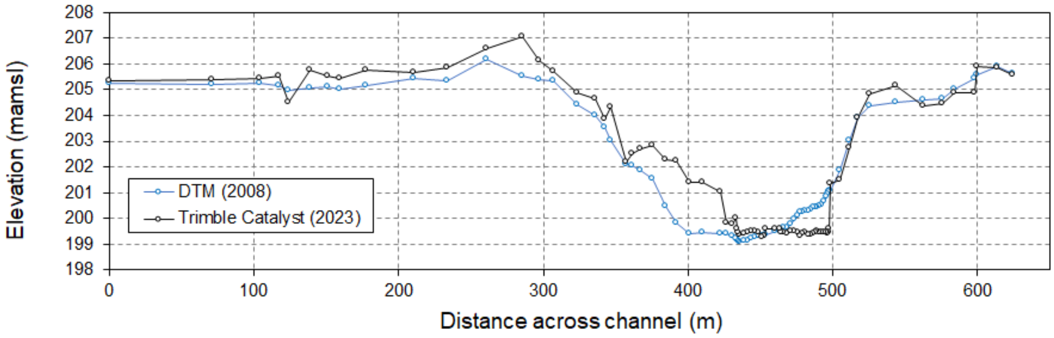

Figure 4.17: Cross-section surveyed across the Luvuvhu River; differences between profiles do not necessarily reflect survey errors, but also geomorphological change (2008 to 2023) that is evident from the underlying aerial photography

Figure 4.18: Trigonometric Beacon 'GWALALI' in the study area near the Luvuvhu-Limpopo Rivers confluence

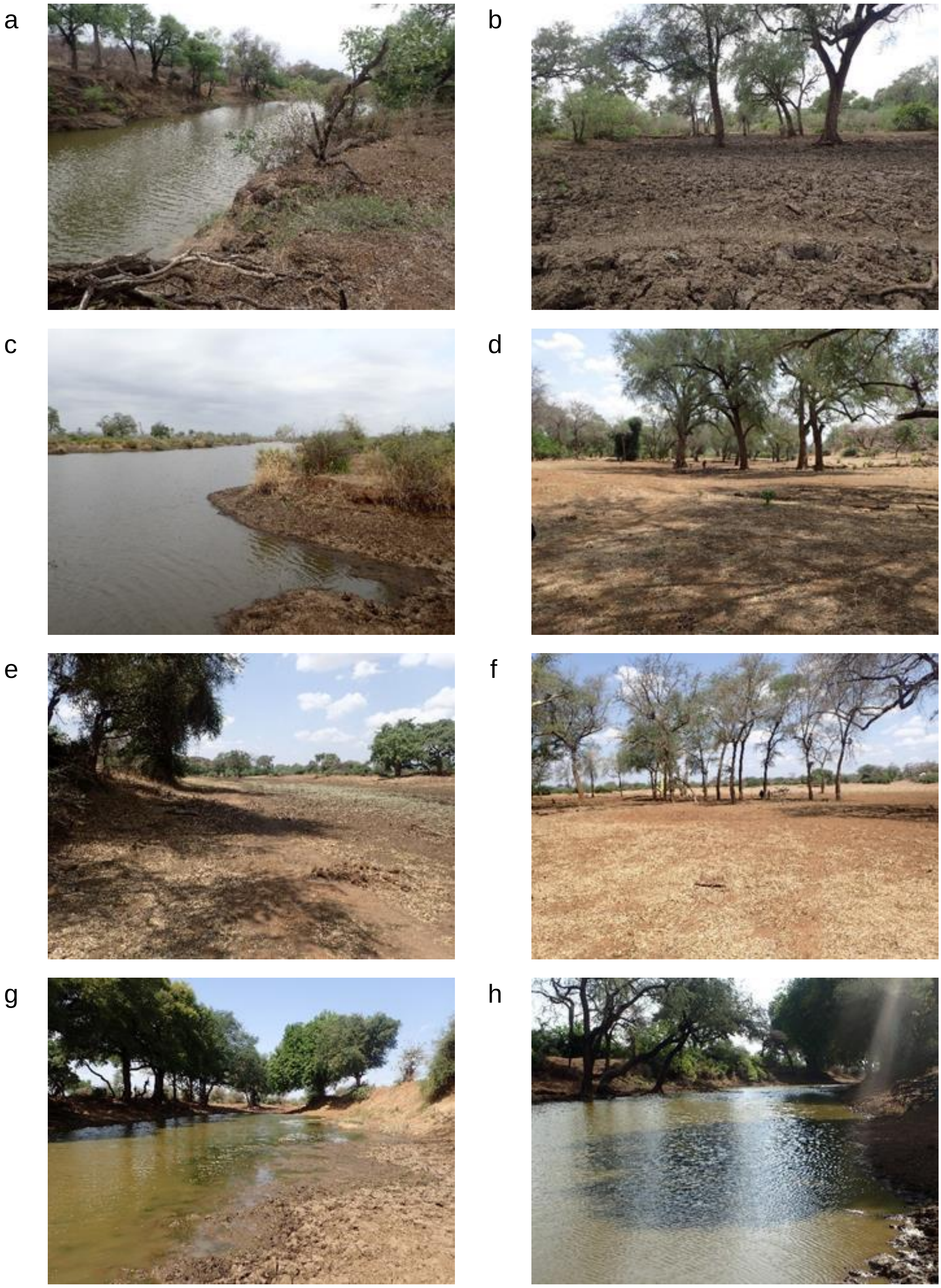

Figure 4.19: Pans on the Luvuvhu River floodplain (October 2022; photographs J. Makenzie) – a) Hapi, b) Shaluka, c) Tlangelani, d) Phamasi, e) Magumugumu, f) Xavele, g) Madwitsombo and h) Mahlonghani

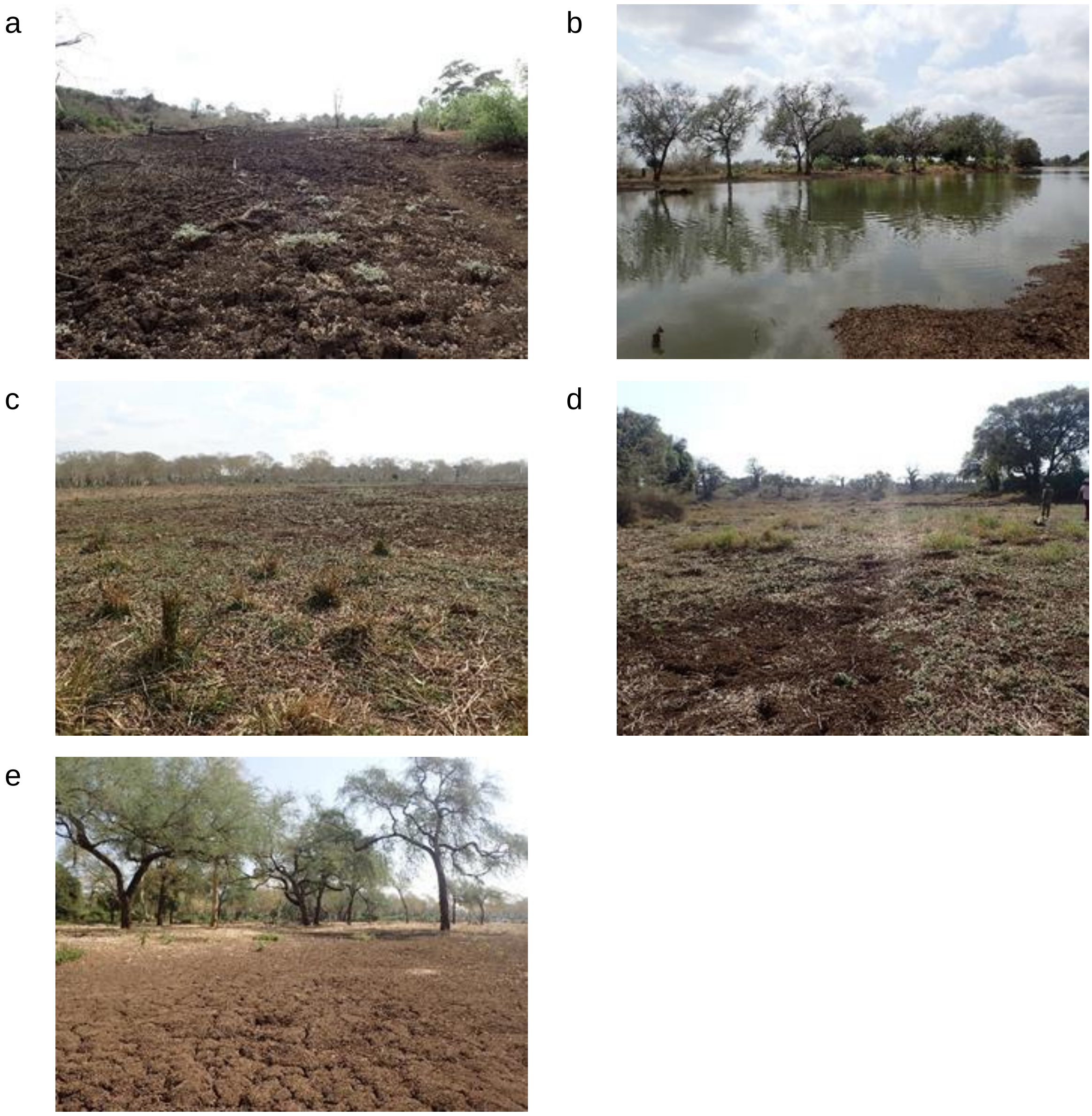

Figure 4.20: Pans on the Luvuvhu River floodplain (October 2022; photographs J. Makenzie); a) Mashila, b) Nwambi, c) Mambvumbvanyi, d) Xagova and e) Gwalana

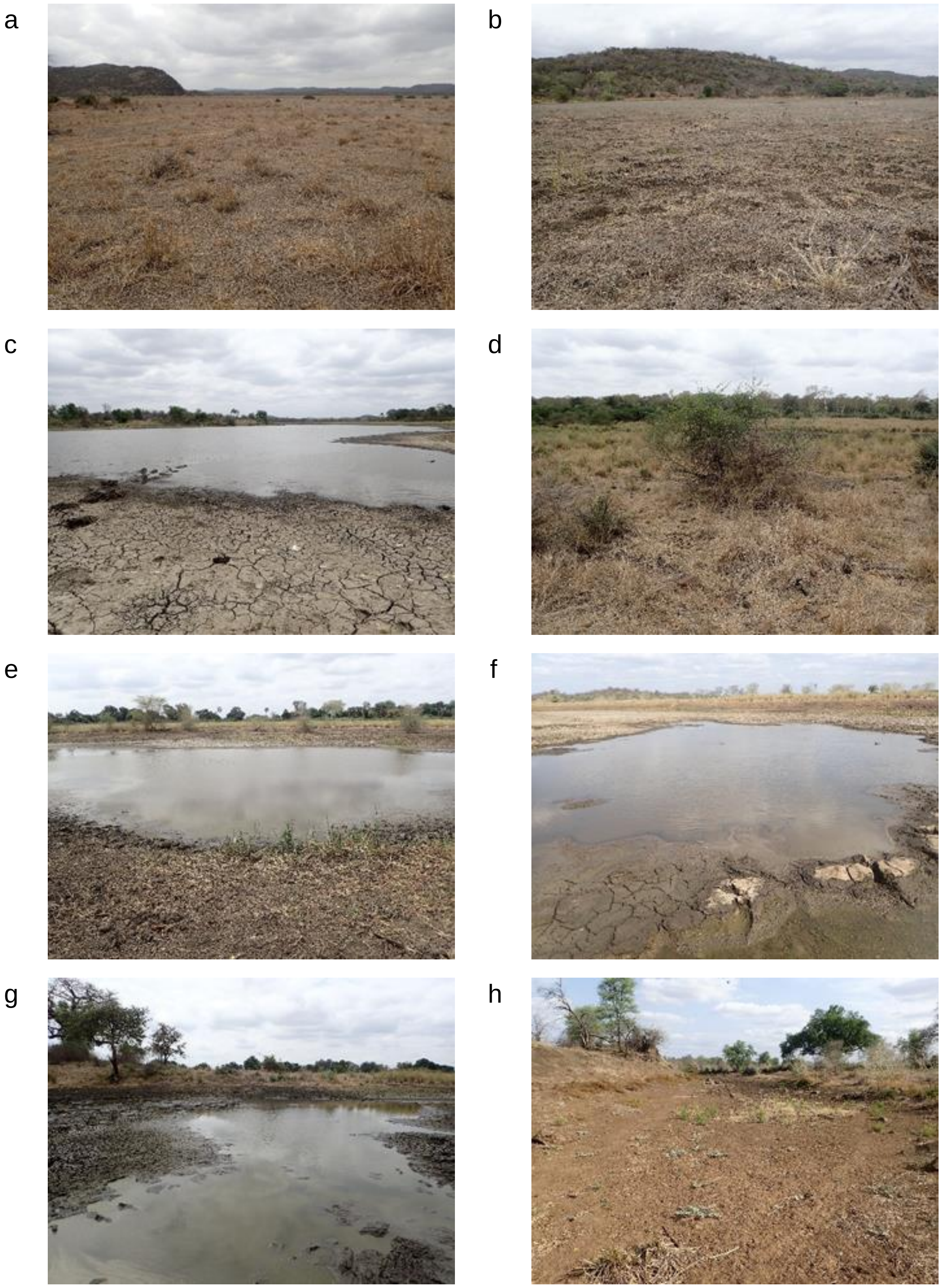

Figure 4.21: Pans on the Limpopo River floodplain (October 2022; photographs J. Makenzie); a) Banyini, b) Xipokonyola, c) Makwadzi, d) Nwaxinavani, e) Hlanalun'we, f) Jachacha, g) Vheme Bendzi and h) Lukangwa

Figure 4.22: Pans on the Limpopo River floodplain (October 2022; photographs J. Makenzie); a) Dakamila, b) Mapimbi, c) Mapimbana and d) Gila

Figure 4.23: Locations of spot elevation measurements taken on the Luvuvhu River floodplain and at the Trigonometric Beacon 'GWALALI' near the Luvuvhu-Limpopo confluence; CRS is Hartebeeshoek94 Lo31

Figure 4.24: Shrinkage and cracking of bed substrate in the Shaluka Pan (seen at most pans on the floodplains, photograph J. Makenzie, October 2022)

4.2.4 Mapping landcover and vegetation type distributions of the Makuleke wetland complex

Knight (2011 cited by Antrobus 2014) classified the vegetation of the Makuleke wetland complex with some species level attributes using a supervised classification (**Figure** 4.25).[42] There appear to be large inaccuracies in the classification, however, and it was therefore necessary to map the landcover and vegetation types along the Luvuvhu and Limpopo River floodplains. The methodology used is similar to that described previously for the Nyl River floodplain (refer to **Section 4.1.3.5**). The study area falls within a single Sentinel 2A scene (two ~110 x 110 km granules). A cloud-free scene towards the end of the 2022 dry season was selected for mapping (23 September 2022), close to the data collection field trip of 17 to 21 October 2022. More-recent dated scenes revealed some burnt grasslands and were therefore rejected for classification. **Figure** 4.26 shows a NCC (top) and FCC (bottom) of the study area.

The stepwise approach used for mapping the landcover and vegetation-types was as follows:

1 Due to differences in water clarity, open water surfaces were extracted separately for the rivers and pans. For the rivers, the Sentinel Water Mask (SWM) of Milczarek *et al.* (undated; **Equation** 4.5) was applied. Values < 0.59 were extracted to create a continuous water surface mask (of the Luvuvhu and Limpopo Rivers), to which all SWM values < 0.62 were confined. For the pans, a combination of the NDVI (**Equation** 4.6) and MNWDI were applied (threshold values of < 0.22 and < 0.55, respectively).

[42] GIS shape files supplied by Romy Antrobus

$$\frac{Blue + Green}{NIR + SWIR1}$$

Equation 4.5

where *Blue* is Band 2, *Green* is Band 3, *NIR* is Band 8 and *SWIR1* is Band 11

$$\frac{NIR - Red}{NIR + Red}$$

Equation 4.6

where *Red* is Band 4

2 The Blue Band (Band 2) was used to extract bare sand and river bed landcovers with a threshold value of > 0.195.
3 The remaining areas were separated into two classes using the NDVI with a threshold value of 0.45, which represent dry vegetation and bare areas (< 0.45) and green (healthy) vegetation (> 0.45). From these two broad NDVI classes, the following 6 classes (some with mixed vegetation lifeforms) were identified using unsupervised classification[43] of the Green, NIR and SWIR1 bands:

- tree
- tree, shrub and sedge
- shrub and grass
- shrub, grass and bare
- grass and bare; and
- bare.

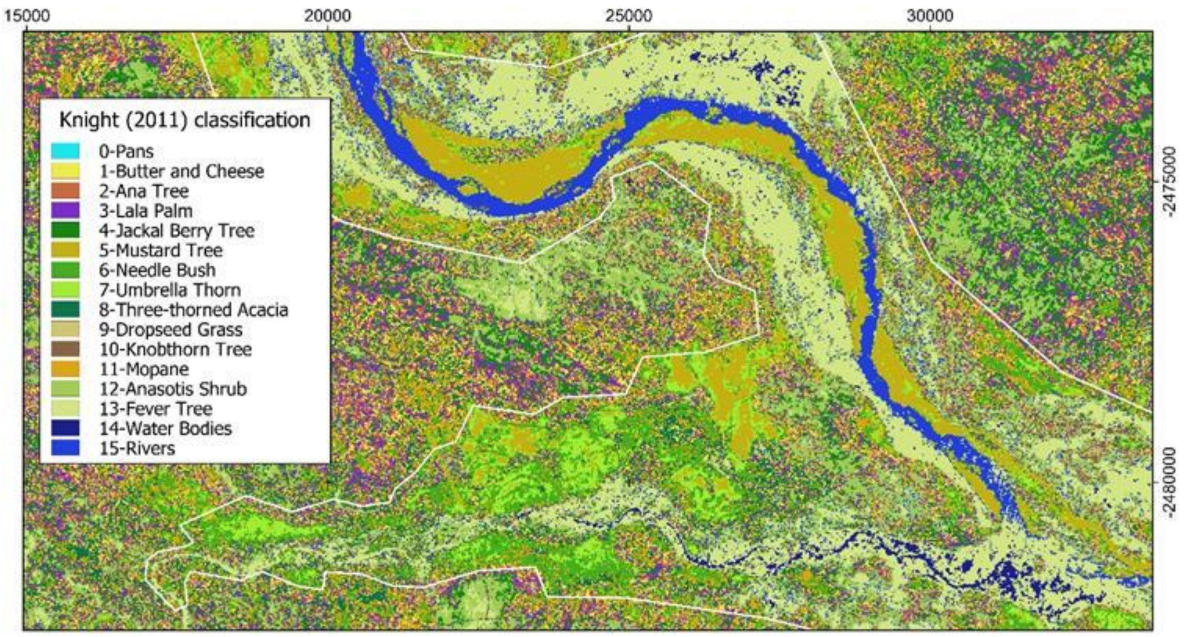

Figure 4.25: Supervised classification image (2011) of the Makuleke wetland complex (Knight 2011, cited by Antrobus, 2014); CRS is Hartebeeshoek94 Lo31

[43] K-means with Hill-Climbing (Rubin 1967)

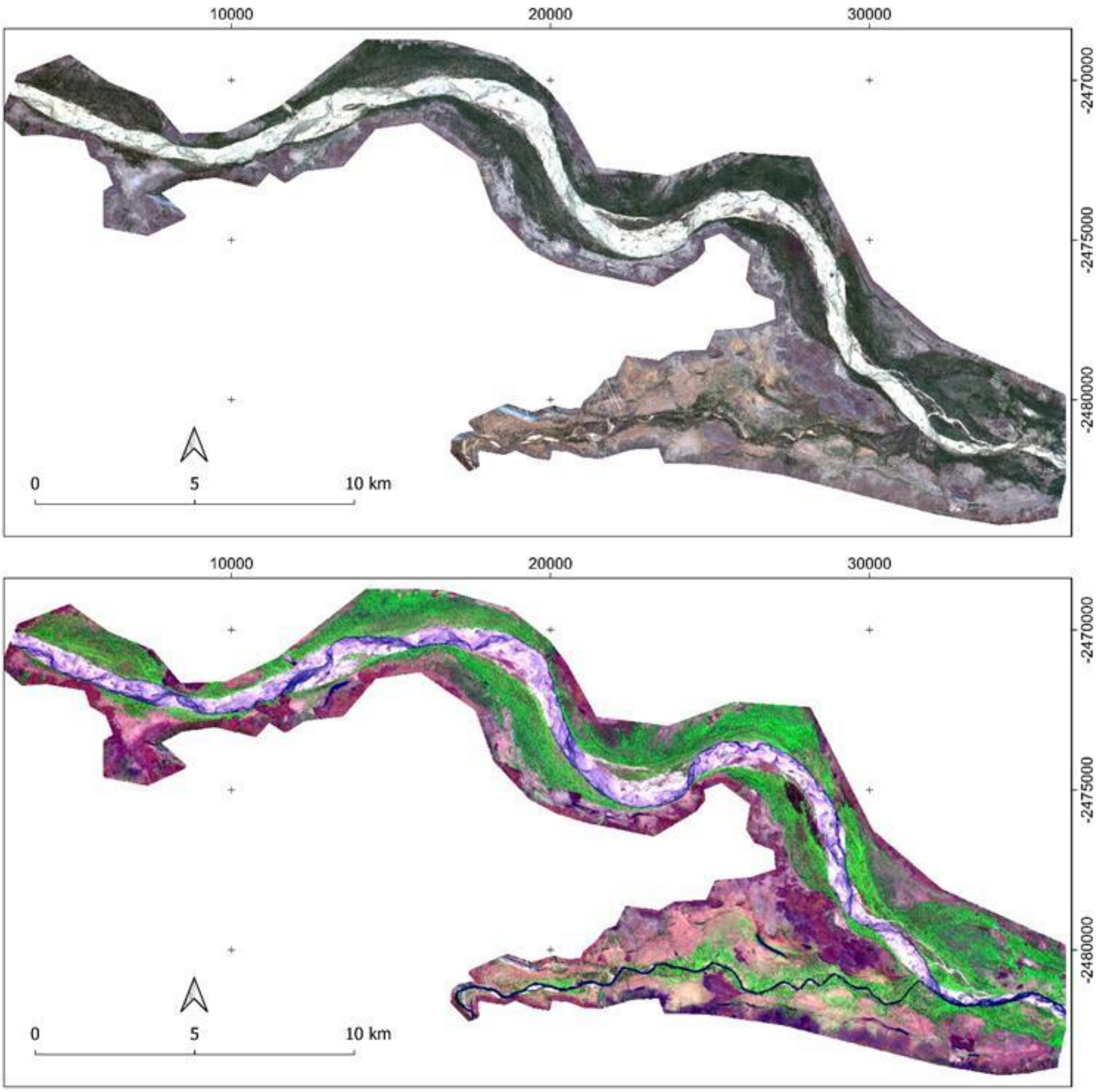

Figure 4.26: NCC (top; Red Green Blue (RGB) = Bands 4, 3, 2) and FCC (bottom; RGB = Bands 11, 8, 3) of the Makuleke wetland complex derived from Sentinel 2 10 m[44] spatial resolution imagery from 23 September 2022; CRS is Hartebeeshoek94 Lo31

As for the Nyl River floodplain, a combination of ground-truthing (**Section 4.2.3.1**) and visual assessments of the distribution of vegetation types from high-resolution NCCs (Bing and Google Earth) and a medium-resolution NCC and FCC (Sentinel 2A) imagery[45] was used to map landcover and vegetation type distributions of the Makuleke wetland complex.

The mapping using Sentinel 2A imagery thus produced eight classes, and the rendered landcover and vegetation-type classification for the Makuleke wetland complex is illustrated in **Figure** 4.27.

[44] excluding SWIR1(Band 11) at 20 m resolution - refer to Table 2.1

[45] This was carried out by the wetland vegetation specialist.

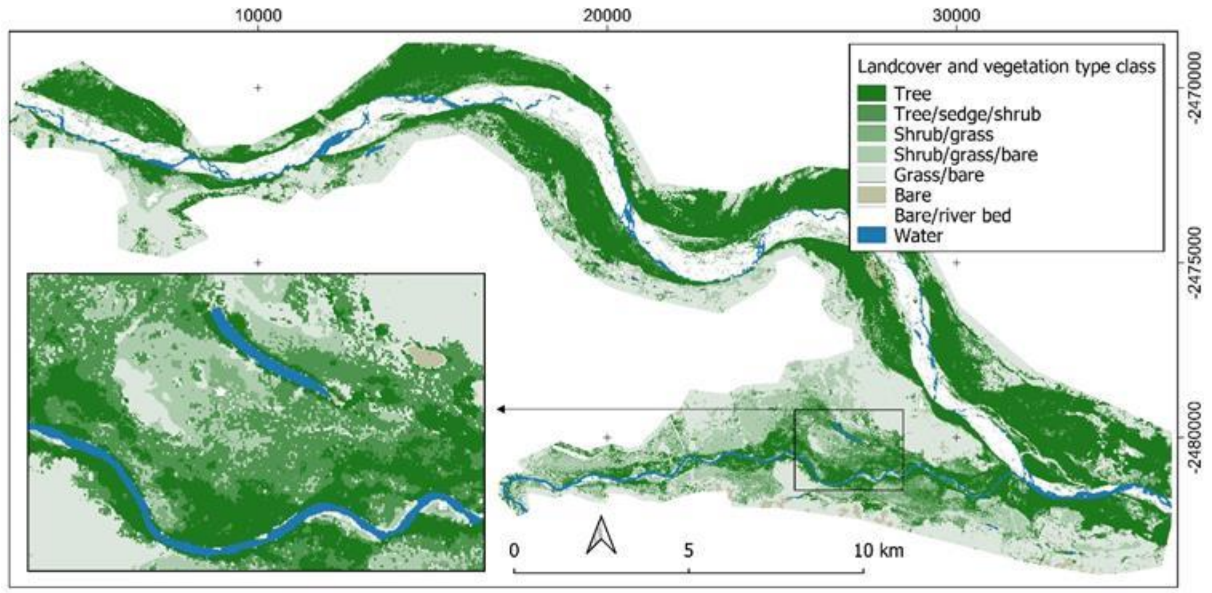

Figure 4.27: Classified landcover and vegetation types of the Makuleke wetland complex, derived from Sentinel 2 10 m spatial resolution multispectral imagery from 23 September 2022; inset shows the Luvuvhu River and Nwambi Pan; CRS is Hartebeeshoek94 Lo31

4.2.5 Hydraulic modelling of the Luvuvhu and Limpopo River floodplains

4.2.5.1 Available hydraulic models of the Luvuvhu floodplain

No suitable hydraulic models appear to have been developed, or are readily available, for the Luvuvhu and Limpopo floodplains in the Makuleke wetland complex. Functionally, from a hydraulics perspective, the river, floodplain and its pans are similar to the Pongola Floodplain, which was modelled two-dimensionally (2-d) using RMA2 (Birkhead *et al.* 2018). Unlike for the Pongola Pans, however, there are no water level data for the Makuleke pans (**Section 4.2.2.2**). Topographic data is also at a substantially lower resolution than the LiDAR survey of the Nyl River floodplain. Furthermore, hydrological data in the form of daily discharge timeseries - particularly for floods that breach the banks of the Luvuvhu and Limpopo Rivers, is coarse[46] (**Section 4.2.6.2**); upstream hydrometric stations on the Luvuvhu and Mutale Rivers are rated to 367 and 135 m^3/s, respectively, which are considerably less than bankfull discharges needed to activate floodplain flows.

Thus, available data do not realistically support the development of a 2-d hydraulic model for the floodplains. Although a 2-d model will provide (coarse) estimates of floodplain depths during infrequent extreme bank-overtopping events (~0.05 to 0.1% time for flows in the range ~750 to 1 000 m^3/s; **Section 4.2.6.2.1**), it will not easily yield pan storage dynamics. The latter requires localised hydrological modelling, or more specifically, the computation of water balances. The Makuleke pans provide critical, albeit ponded[47], aquatic habitat and need to be adequately addressed in this study. For these reasons, a 1-d HECRAS hydraulic model, similar to that developed for the Nyl River Floodplain (**Section 4.1.2.3**) was developed to predict the combination of flow regimes in the Luvuvhu and Limpopo Rivers that

[46] disaggregated monthly flows

[47] except during extreme bank-overtopping flood events

initiate floodplain flows for different regions of the study area. This gives the necessary input for modelling depth timeseries for selected study pans, discussed in **Section 4.2.6**.

4.2.5.2 Conceptual understanding of water movements across the Luvuvhu floodplain that affect pan storage dynamics

Figure 4.28 is a conceptual illustration of the water sources and flow paths across the Luvuvhu floodplain that affect pan storage dynamics, with the locations indicated of the four EWR pan sites; Nwambi, Mambvumbvanyi/Reedbok, Hapi and Tlangelani. All the pans in the Makuleke wetland complex are temporary, and have dried-up historically, as evidenced from the historic satellite imagery (**Section 4.2.6.1**) and personal communications, *viz*. Sandra Visagie[48] (re. Nwambi Pan during severe droughts) and Johan Turner[49]. The Nwambi and Hapi Pans are, however, the deepest and 'least-intermittent'.

It is essential to include the influence of the Limpopo River (**Figure** 4.29**)** when considering the hydrodynamics of the Luvuvhu floodplain, since it backfloods up into the lower Luvuvhu River under certain combined flow regimes.

The main water sources that active floodplain flows and concomitant inflows to pans along the Luvuvhu Floodplain are (**Figure** 4.28):

- river bank overtopping at multiple levee breaches along the Luvuvhu
- backup from the Limpopo River into the Luvuvhu,[50] which leads to both bank overtopping and backflooding of the 'Nwambi channel (**Figure** 4.30) that connects Mambvumbvanyi/Reedbok and Nwambi Pans with each other and the Luvuvhu River
- runoff from local sub-catchments, the largest of which lie south of the study area in the so-called Vlakteplaas[51] area and drain into the southern floodplain
- direct rainfall.

The hydrodynamic model incorporated six DRIFT-Luvuvhu EWR sites (see **section 6.2**):

- pan sites on the Luvuvhu floodplain for which water balances are computed:
  - 19_Nwambi, 20_Mambvumbvanyi/Reedbok, 21_Hapi and 22_Tlangelani
- river sites included that act as important hydraulic controls on flooding of the floodplain:
  - 23_Luvuvhu3 the large pool at the confluence of the Luvuvhu and Limpopo Rivers
  - 18_Luvuvhu2, a river cross-section upstream of Pafuri bridge that is the uppermost levee breached by floods in the Luvuvhu River that flow onto the floodplain.

[48] former Park Ranger, Pafuri area (KNP)
[49] former guide at Return Africa, Makuleke Contractual Park
[50] results of the hydraulic modelling (Section 0) indicate that the Limpopo's flooding influence extends ~6km upstream of the confluence
[51] translation: 'flat farm'

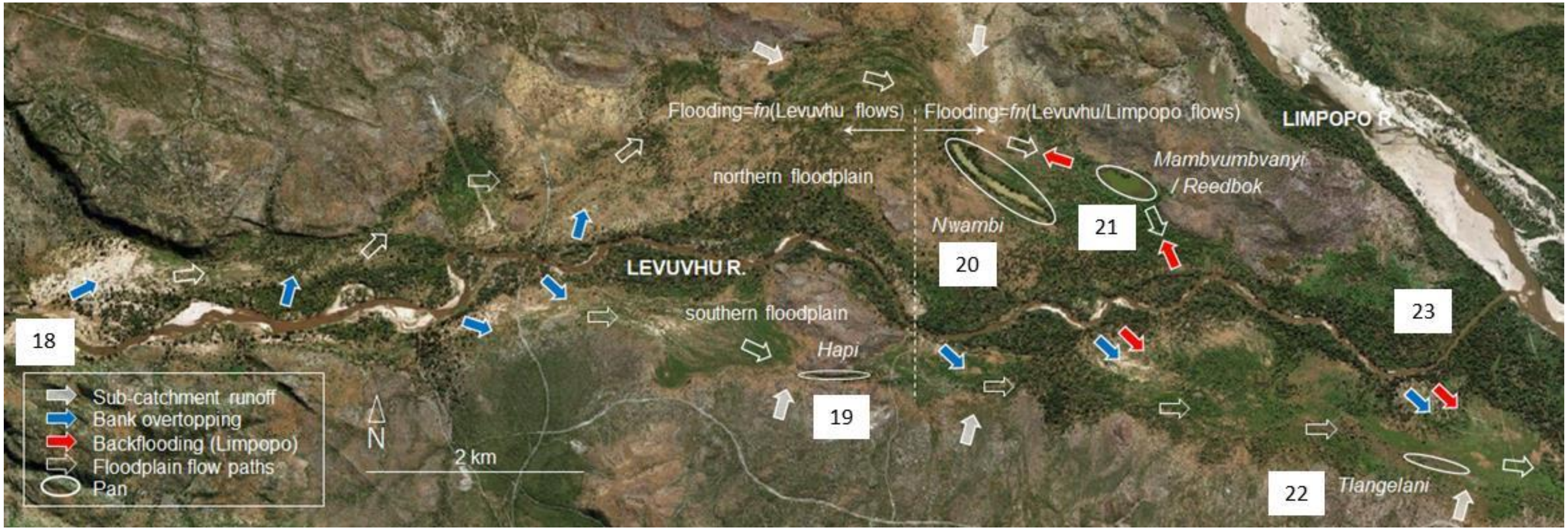

Figure 4.28: Water sources (*viz*. sub-catchment runoff, overtopping of the Luvuvhu River's banks and backflooding from the Limpopo River) and flow paths across the Luvuvhu floodplain that result in filling of the pans; the EWR sites in DRIFT-Luvuvhu are numbered: 18_Luvuvhu2, 19_Hapi, 20_Nwanbi, 21_Mambvumbvanyi, 22_Tlangelani, 23_Luvuvhu3

Figure 4.29: Top: Limpopo River at Crooks Corner in October 2022 – flow is from the Luvuvhu River; bottom: flood in February 2023

Figure 4.30: Left: Luvuvhu River facing upstream and the Nwambi channel entering on the left bank (arrow); right: facing upstream along the Nwambi channel at its confluence with the Luvuvhu River

4.2.5.3 HECRAS Luvuvhu floodplain model

The following approach was adopted to develop a HECRAS 1-d model for the Luvuvhu and Limpopo Rivers and adjacent floodplains:

- cross-sections were positioned (in GIS) on the DTM of the Luvuvhu and Limpopo Rivers floodplains[52] to coincide with locations where levees are breached (visible on Bing historical satellite imagery *ca*. 2013)
- the breach locations were identified and accurately surveyed (**Section 4.2.3.1**)
- cross-sections were 'bent' where necessary to be ~orthogonal to the direction of flow in the river and on the floodplain (**Figure** 4.31) and the river centrelines were digitised
- cross-section geometries were extracted from the DTM (described in **Section 4.2.2.1**)
- overflow weirs were used to simulate the effects of bank overtopping from the Luvuvhu River, which required dividing the extracted cross-sections into left and right floodplains so they could be treated as separate 'floodplain channels':
    - the right floodplain channel[53] is termed the 'Hapi River' on various maps, and the left floodplain channel downstream of the Nwambi Pan, the 'Nwambi channel'[54]
- weirs were positioned between selected adjacent cross-sections, which allowed these structures to be temporarily excluded during model development - since numerical issues were experienced in attaining convergent solutions for some weir locations, flows and coefficient values:
    - weir coefficients were typically 0.10, which applies to overland flow
- (standard) levee structures were used for the Limpopo cross-sections
- bank station locations, which may be used to partition cross-channel flow resistance values, were digitised using recent GE™ imagery to identify and demarcate the locations of tree lines or regenerated riparian vegetation post-2013 flooding
- flow resistance values (Manning's *n*) of 0.030 and 0.10 were applied to the active channel and vegetated banks or floodplains, respectively
- for the Limpopo River the flow resistance was varied from 0.035 in the channel to 0.13 for overbank flooding onto the floodplain
- bespoke software was used to convert georeferenced geometric data from GIS output to ASCII text format for import to HECRAS
- boundary conditions in the model included inflows upstream (Luvuvhu and Limpopo Rivers) and a uniform slope (0.00087 m/m derived from the DTM) downstream of the confluence.

There are very few hydraulic data for model calibration, particularly discharges, which are the product of disaggregated monthly hydrological modelling, which in turn, is based on extrapolated gauge data (**Sections 4.2.2.2** and **4.2.6.2.1**). Thus, the HECRAS 1-d hydraulic model was largely parameterised using *inter alia* characteristic flow resistance values from experience and the literature. The steady-state model was applied to determine flows in the Luvuvhu and Limpopo Rivers, as appropriate to the location of the specific study pan, that would result in bank overtopping and backflooding up the Nwambi channel, and initiate floodplain flows with associated pans inflows (from upstream) and backflooding (from downstream).

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[52] since the right Luvuvhu floodplain (Hapi 'channel') continues downstream beyond the SA-Mozambique Border and extent of the DTM (Figure 4.12)

[53] more accurately, the lowest elevation laterally across the floodplain

[54] Johna Turner, pers. comm.

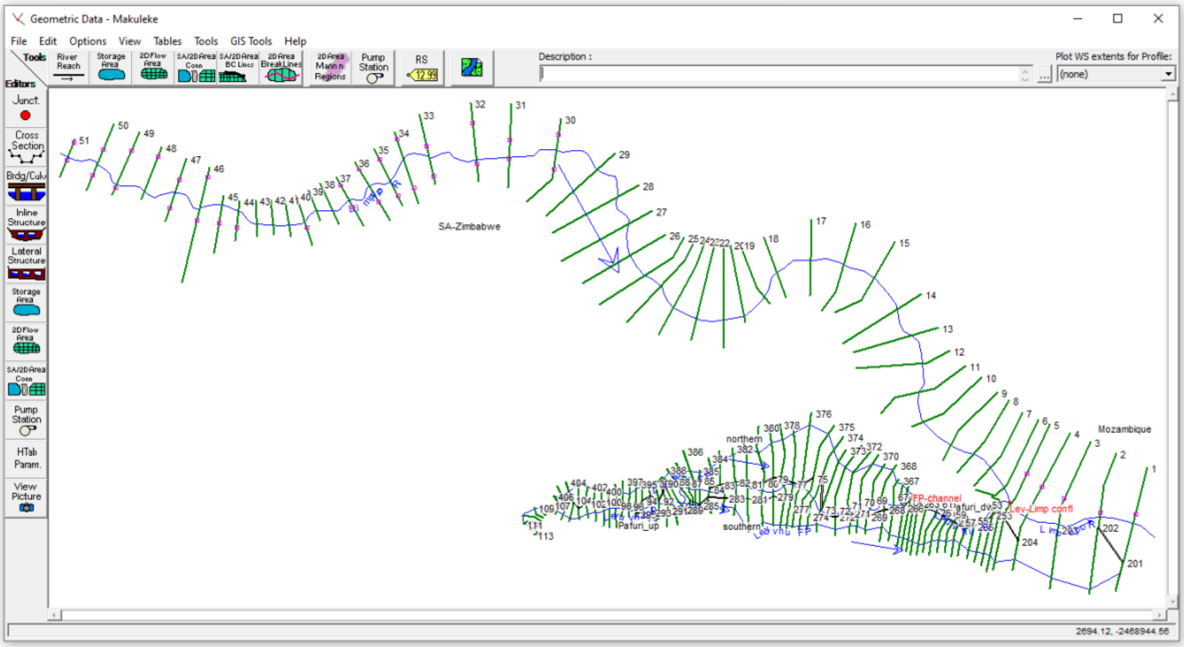

Figure 4.31: Georeferenced geometric data in HECRAS

Figure 4.32 provides plots of the modelled relationships between discharge in the Luvuvhu and Limpopo Rivers that result in filling of the pans. For the Nwambi Pan, flows in the Luvuvhu River exceeding ~750 m^3/s are predicted to result in inflows (from upstream) – irrespective of flows in the Limpopo. Backfilling along the Nwambi channel (**Figure** 4.28**, Figure** 4.30) depends, however, on flows in both rivers. For example, when the discharge in the Limpopo exceeds ~3 500 m^3/s, backfilling will occur even with minimal flow in the Luvuvhu; the converse applies when the Luvuvhu's discharge exceeds ~350 m^3/s. These relationships were used in the pan depth timeseries modelling in **Section 4.2.6**.

4.2.5.4 Pool habitat upstream of the Limpopo River confluence

Although there are small, isolated pools of sufficient depth for hippopotami along the length of the Luvuvhu River in the KNP, the ~800 m stretch immediately upstream of the Limpopo confluence provides reasonably permanent habitat whilst the Luvuvhu remains perennial (**Figure** 4.33). This reach is critical during droughts for *inter alia* large population of hippopotami and crocodiles, when pans are dry and flows in the Luvuvhu River are low[55]. Low flows in the Luvuvhu River are largely maintained through releases from upstream dams. Available historical satellite imagery indicates that this lower stretch of river is generally well inundated (bank to bank) and appears to be deeper than further upstream where the channel planform is braided during the low flow season. To ascertain why this is so, the hydraulic characteristics of this lower reach were analysed using the HECRAS 1-d model. This indicated the development of a so-called 'M2' gradually-varied water surface profile (e.g. James 2020) upstream of the confluence during high flows when the discharge (and water level) in the Luvuvhu is notably higher than that in the Limpopo. This results in locally increased shear stresses (and

[55] Richard Sowry (section ranger at Pafuri in KNP) pers. comm.

concomitant erosion) immediately upstream of the confluence, compared with further upstream. While the asynchronicity of flooding events in the Luvuvhu and Limpopo cannot realistically be managed, this elucidates the importance of maintaining an adequate flooding regime in the Luvuvhu to maintain critically important depth habitat along this lower reach.

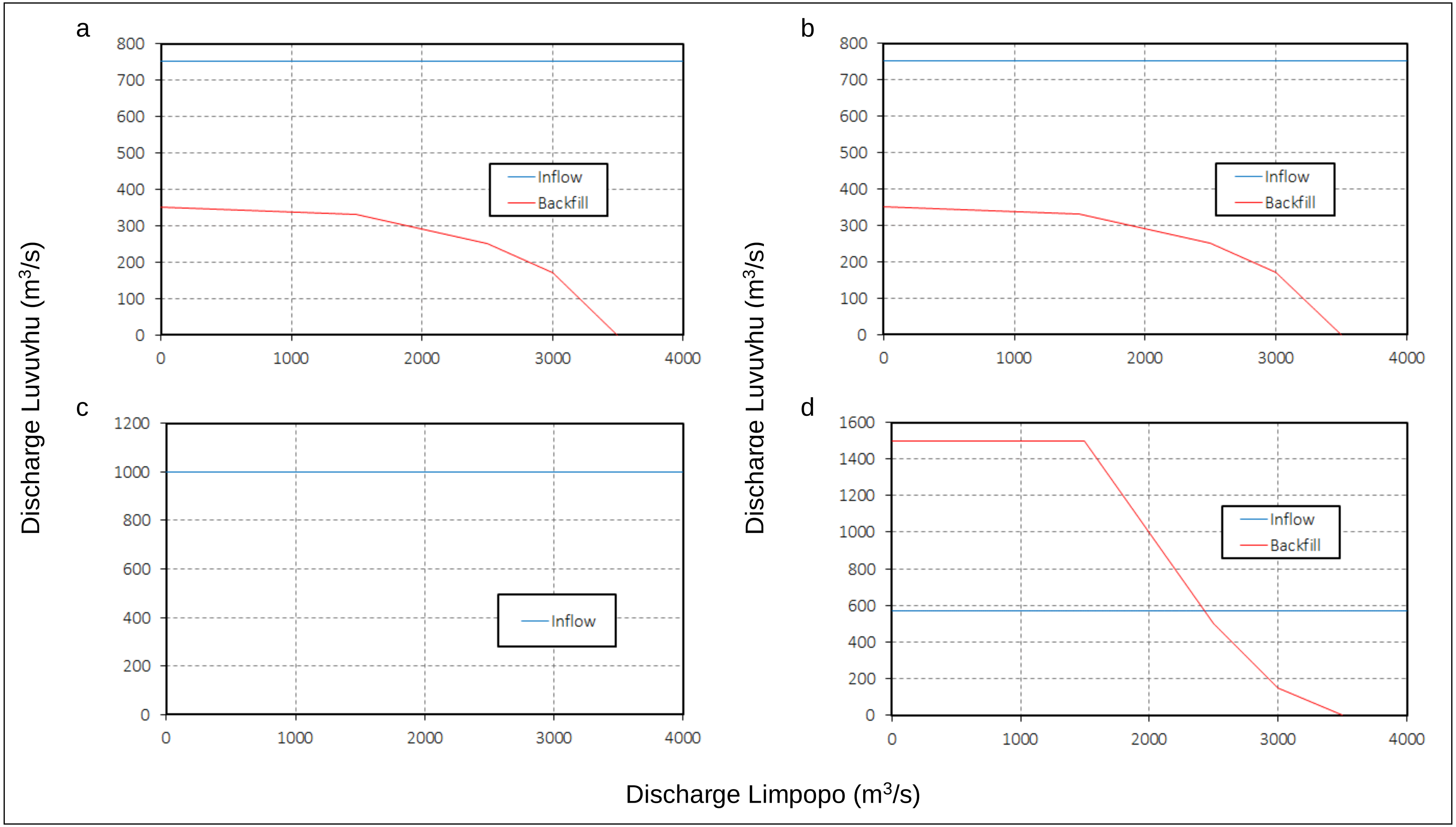

Figure 4.32: Modelled governing inflow (from upstream) and backfilling (from downstream) arising from levee breaching along the Luvuvhu River, leading to the filling of pans: a) Nwambi, b) Mambvumbvanyi/Reedbok, c) Hapi, d) Tlangelani; for these pans excluding Hapi, backfilling also depends on flows in the Limpopo River

Daily shear stress timeseries were computed for two locations (for the Naturalised, PES and Future flow scenarios for the lower Luvuvhu River) immediately upstream of the confluence and at the head of this reach. The difference in shear stress between the two locations provides the additional[56] potential for entraining sediment from the bed, to thus maintain a deeper lower reach. These data were loaded into DRIFT-Luvuvhu as one of the hydraulic indicators so this relationship and its influence on habitat for hippopotami in the lower Luvuvhu River could be captured at the river site 23_Luvuvhu3.

Figure 4.33: The ˜2.5-km reach immediately upstream of the Limpopo confluence showing the ~800 m long deep pool (GE^{TM} imagery dated 06/2007)

4.2.5.5 River site upstream of Pafuri Bridge on the Luvuvhu River

The HECRAS Makuleke model described in **Section 4.2.5.3** was also applied to synthesize the hydraulic characteristics for the river site surveyed ~900m upstream of Pafuri Bridge (at river EWR site 18_Luvuvhu2, **Figure** 4.17**)**. This is the first point where overbank flooding takes place onto the Luvuvhu River floodplain (**Figure** 4.28). A rating relationship (**Figure** 4.34) and text tables (*viz*. relationships between discharge and ecologically relevant hydraulic parameters such as depth, wetted perimeter, etc.) were derived for further processing in the DRIFT-Luvuvhu.

[56] i.e. exceeding that being transported from upstream

a

b

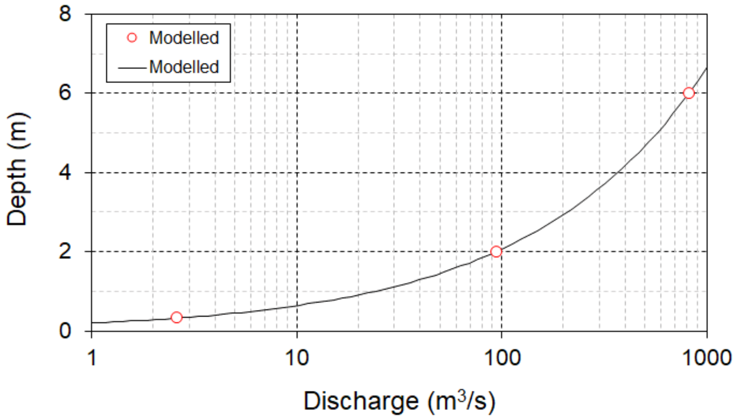

Figure 4.34: a) Photograph of the sand-bed river at a site on the lower Luvuvhu ~900m upstream of Pafuri Bridge (photograph J. Makenzie); b) modelled rating relationship

4.2.6 Modelling depth timeseries for selected pans

4.2.6.1 Approach and methodology

As discussed previously (**Section 4.2.5.1**), hydraulic modelling cannot easily output the temporal storage (or associated depth) behaviour of the pans on the Luvuvhu River floodplain, which provide critical aquatic habitat to a range of fauna - particularly during the dry season. This required localised hydrological modelling, or more specifically, the computation of water balances - specific to each study pan. Although this requirement was not initially envisaged as part of this study, its importance necessitated its inclusion and involved developing:

- stage-volume-area relationships, and estimates of minimum bed and full supply levels (fsl) for the pans, which were derived from topographical data and bathymetric surveys (**Sections 4.2.2.1** and **4.2.3.1**)
- the combination of discharges in the Luvuvhu and Limpopo Rivers that breach the levees and initiate floodplain inundation and associated inflows to, or backfilling of, the pans, provided from the hydraulic modelling component
- estimates of rainfall and runoff from local sub-catchments, and evapotranspiration (**Section 4.2.6.2**).

The water balance involved the computation of pan storage (i.e. water volume) and water depth at a daily timestep. In addition to the main data inputs described above, model development assumed that bank overtopping events leading to floodplain flows completely fill the relevant pans. Additional inputs required were:

- estimates of the proportion of pan area which contributes to runoff from direct rainfall
- for certain pans (e.g. Hapi), water level drawdown after a filling event appears to be reasonably rapid[57], and could not be accounted for (in the water balance) by evaporation losses; consequently, a seepage loss function was incorporated that applies a maximum seepage loss (at fsl) and a decay coefficient; this is consistent with the high clay content generally noted on the beds (e.g. **Figure** 4.24), which would act to reduce seepage with decreasing depths below fsl.

Figure 4.35 to **Figure** 4.42 show imagery (satellite and aerial photographs) from 2005 to 2023 for the four pans modelled and provided a useful source of long-term, though intermittent, data against which the characteristic modelling of pan storage dynamics could be assessed. Parameter values in the water balance computations were adjusted to achieve reasonable overall temporal behaviour when compared to the ~areas of pan inundation (i.e. dry, low, medium and high). The aerial imagery also attests to the fact that all the floodplain pans on the Luvuvhu River floodplain are temporary.

[57] as noted from aerial imagery in Figure 4.39 and Figure 4.40

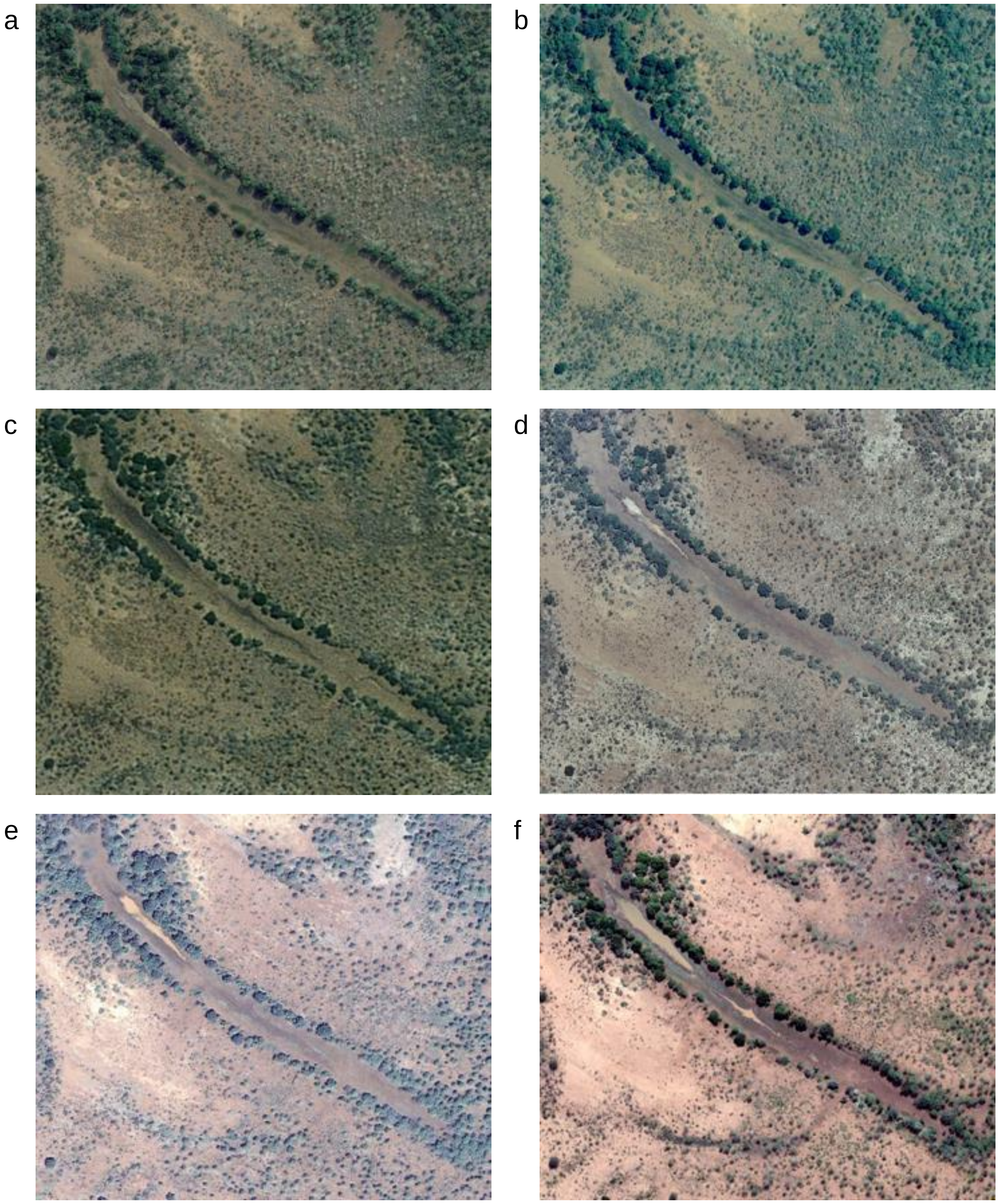

Figure 4.35: Aerial imagery (GE™ and aerial photos) of the Nwambi pan (2005 to 2012): a) 17/05/2005, b) 15/08/2005, c) 05/10/2005, d) 30/11/2008, e) 01/02/2010, f) 04/10/2012

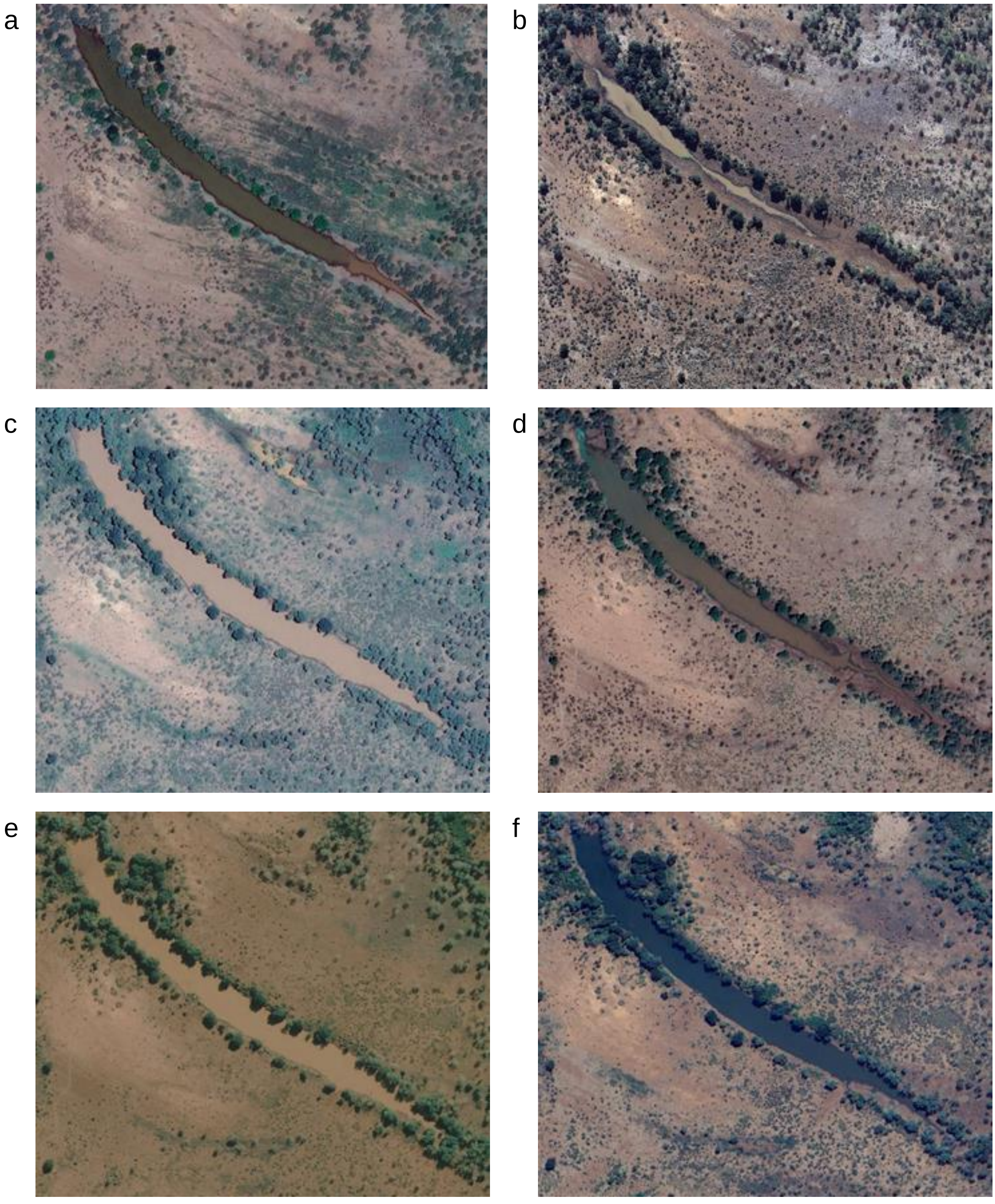

Figure 4.36: Aerial imagery (GE™ and aerial photos) of the Nwambi pan (2013 to 2023): a) 06/10/2013, b) 20/06/2015, c) 27/03/2016, d) 20/11/2018, e) 01/06/2020 and f) 23/04/2023

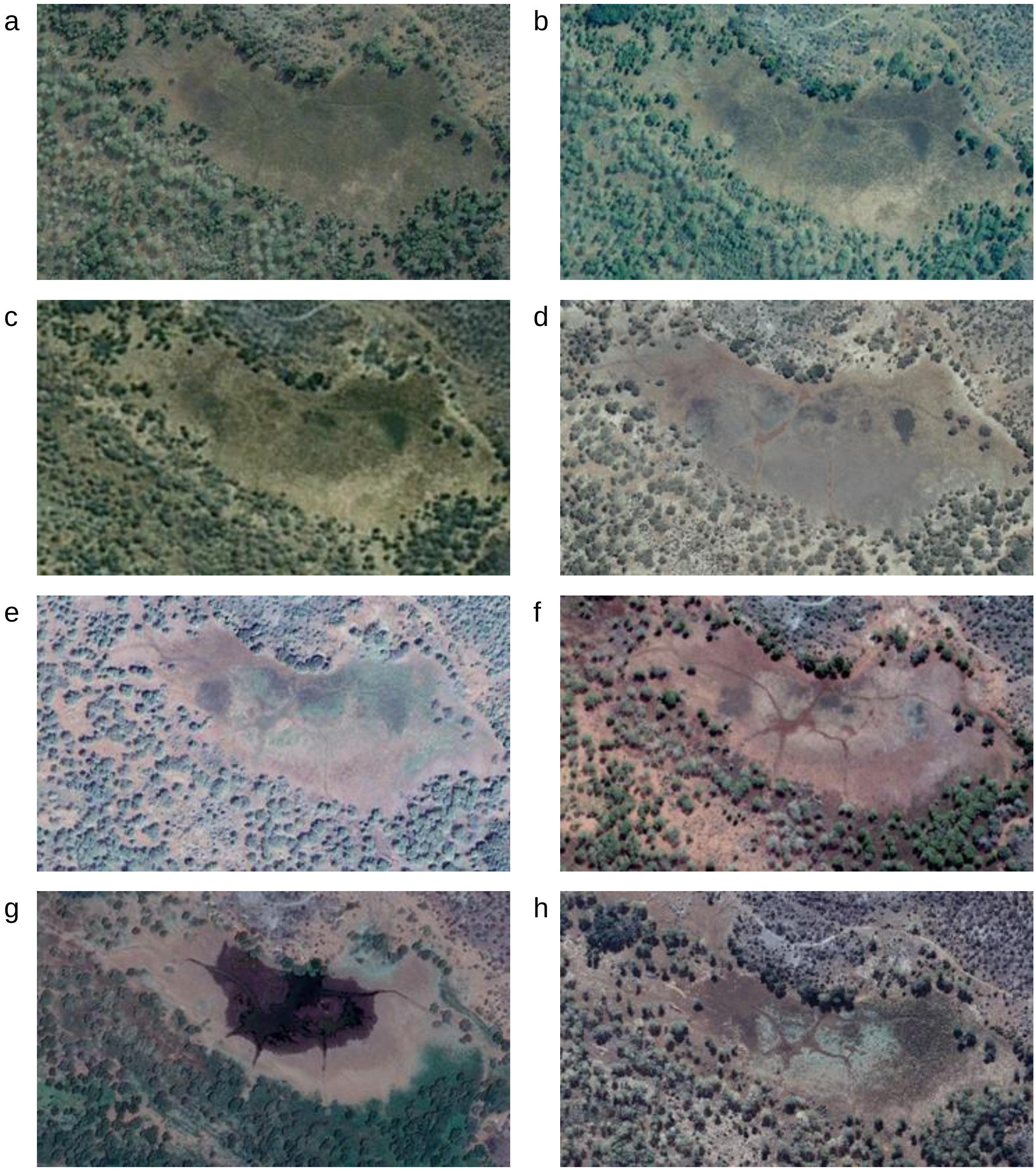

Figure 4.37: Aerial imagery (GE^{TM} and aerial photos) of the Mambvumbvanyi/Reedbok pan (2005 to 2015): a) 17/05/2005, b) 15/08/2005, c) 05/10/2005, d) 30/11/2008, e) 01/02/2010, f) 04/10/2012, g) 06/10/2013, h) 20/0/2015

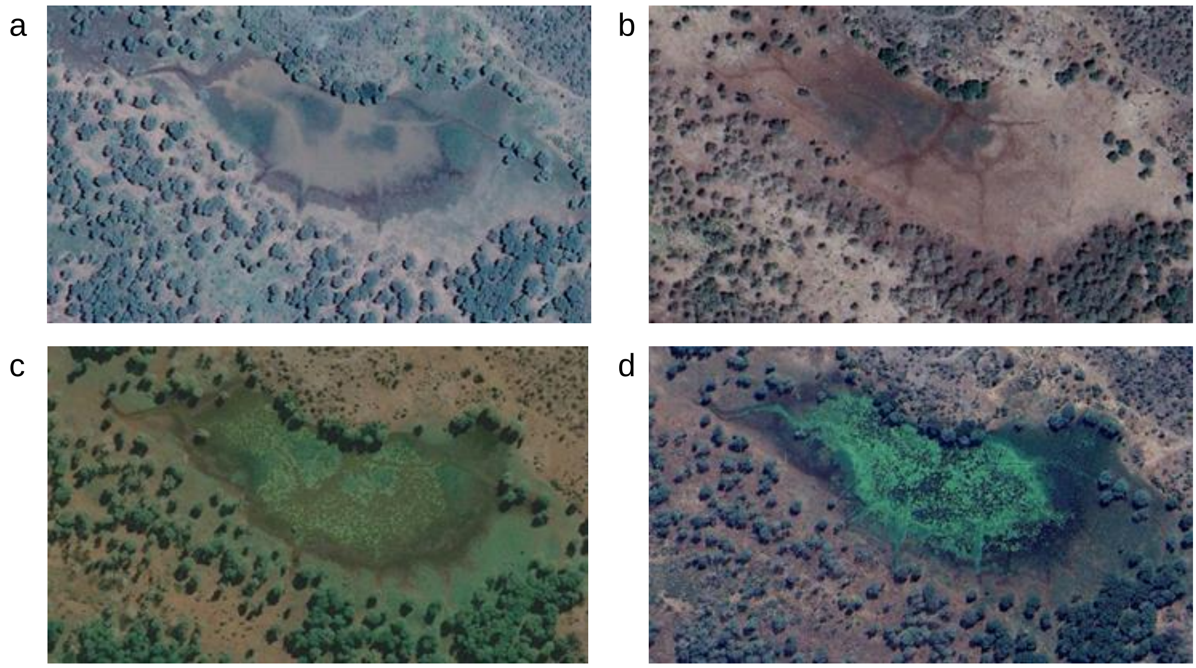

Figure 4.38: Aerial imagery (GE™ and aerial photos) of the Mambvumbvanyi/Reedbok pan (2016 to 2023): a) 27/03/2016, b) 20/11/2018, c) 01/06/2020, d) 23/04/2023

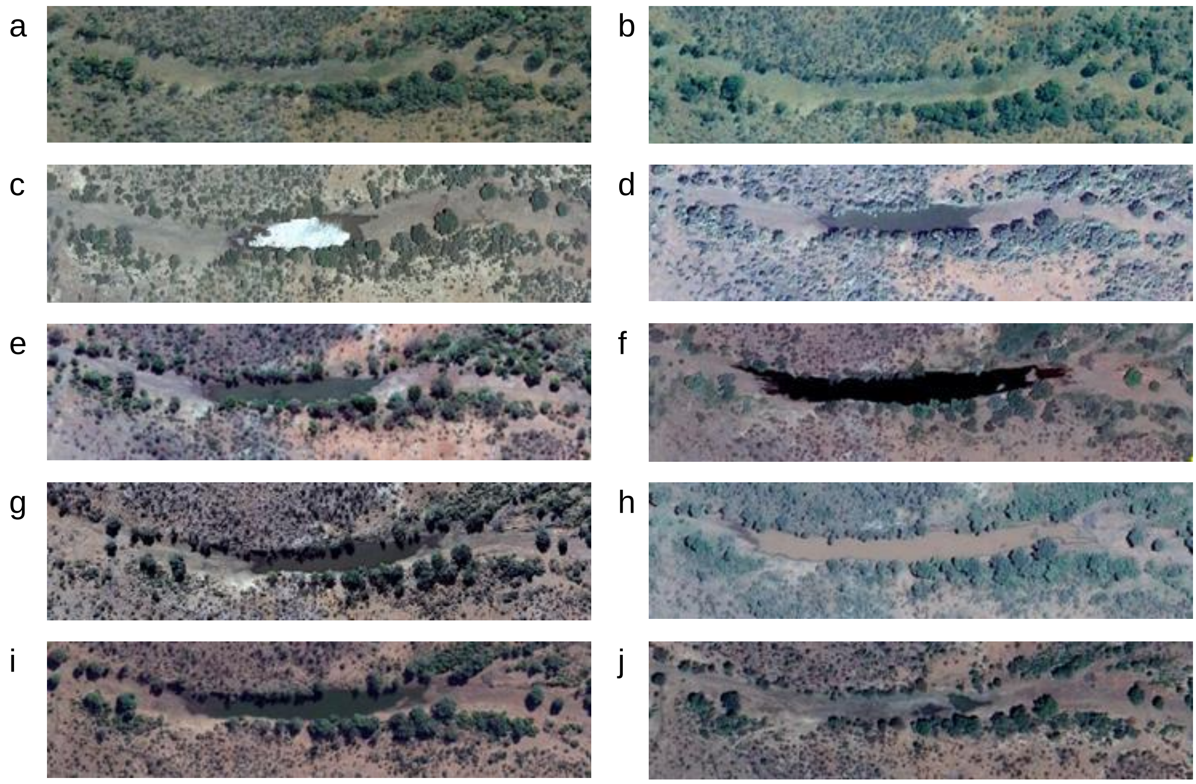

Figure 4.39: Aerial imagery (GE™ and aerial photos) of the Hapi Pan (2005 to 2018): a) 17/05/2005, b) 15/08/2005, c) 30/11/2008, d) 01/02/2010, e) 04/10/2012, f) 06/10/2013, g) 20/06/2015, h) 27/03/2016, i) 04/06/2017, j) 20/11/2018

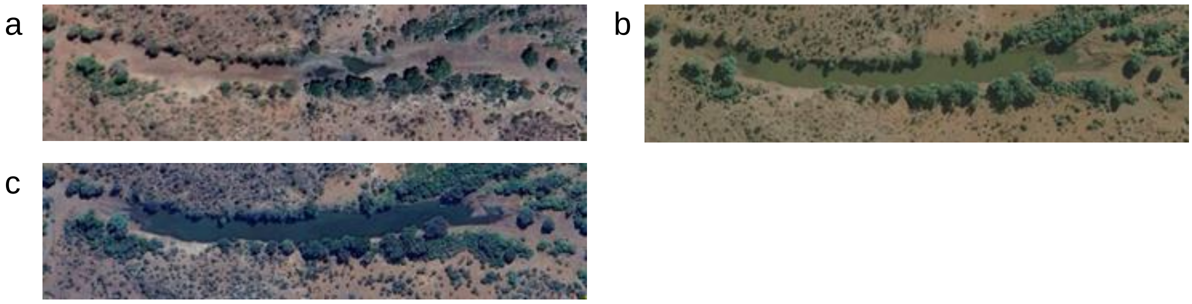

Figure 4.40: Aerial imagery (GE™ and aerial photos) of the Hapi Pan (2019 to 2023): a) 02/05/2019, b) 01/06/2020 and c) 23/04/2023.

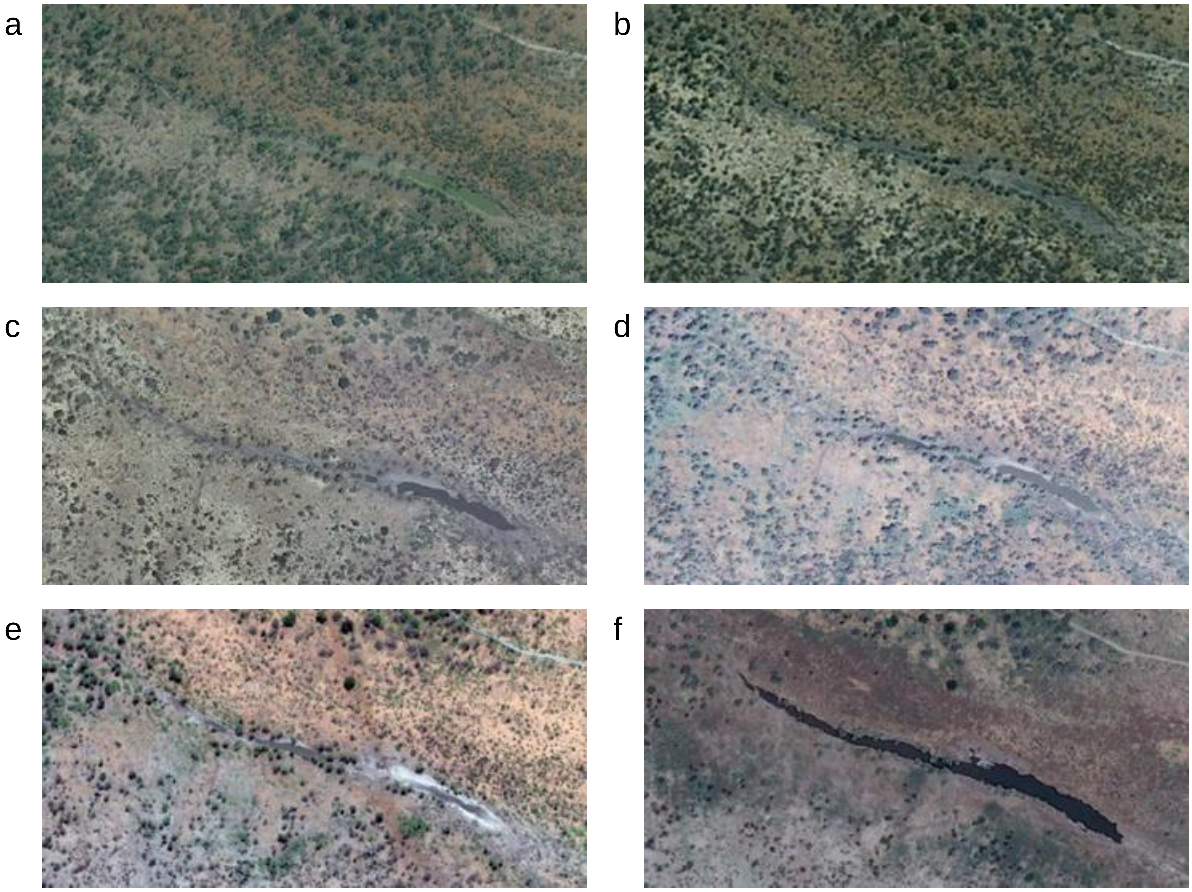

Figure 4.41: Aerial imagery (GE™ and aerial photos) of the Tlangelani Pan (2005 to 2013): a) 17/05/2005, b) 06/2007[58], c) 30/11/2008, d) 01/02/2010, e) 04/10/2012, f) 06/10/2013

[58] day not specified

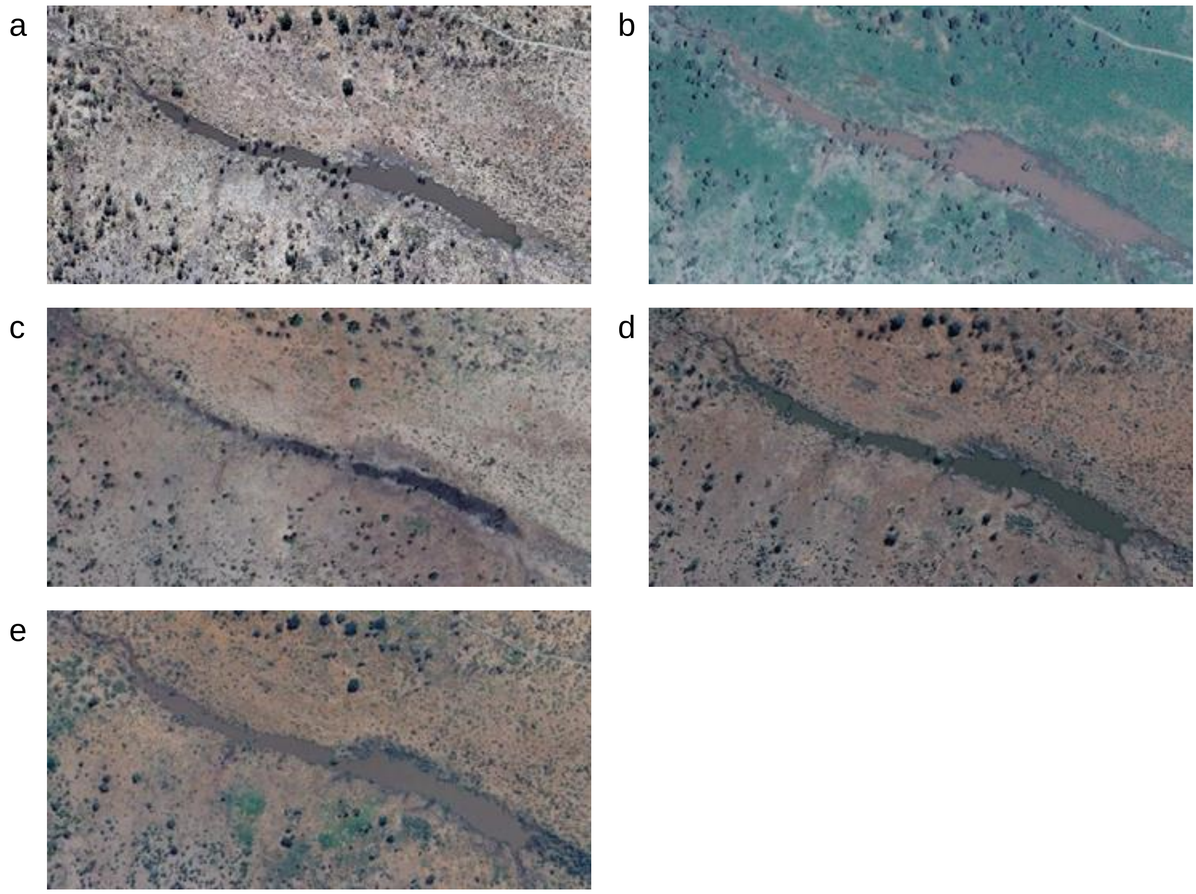

Figure 4.42: Aerial imagery (GE^{TM} and aerial photos) of the Tlangelani Pan (2015 to 2023): a) 20/06/2015, b) 27/03/2016, c) 20/11/2018, d) 06/01/2020 and e) 23/04/2023

4.2.6.2 Hydrological timeseries data

4.2.6.2.1 Discharge timeseries for the Luvuvhu and Limpopo Rivers

The hydrological modelling for the rivers component of this study (River Assessment (Volume 2): Data Collection and Analysis Report) was extended to provide hydrological timeseries for Naturalised and PES flow scenarios at a daily time-step for the period 1925 to 2021 for the lower Luvuvhu River. This required combing the extrapolated daily discharge timeseries for the river EWR sites 12_Luvuvhu upstream of the Luvuvhu River floodplain (using a catchment area factor of 1.366) and its incremental tributary on the Mutale River, 14_Mutale2. Since hydrological modelling of the Limpopo River was not part of this study monthly timeseries data were obtained from the LIMCOM study (O'Brien 2022) that extend from 1925 to 2011. Since all the hydrological inputs into DRIFT-Luvuvhu must be at the same time-step and for the same period it was necessary to shorten the Luvuvhu River hydrological record by ten years from 2021 to 2011 and to disaggregate the monthly flows for the Limpopo River to a daily time-step. Gauged flow data are available for the Limpopo River after 1955 from the DWS hydrometric station at Beit Bridge (A7H004/8), located ~158 km upstream of the Luvuvhu River confluence. These records were infilled for missing periods and used to disaggregate the modelled monthly volumes to provide a 56-year concatenated daily timeseries (Naturalised and PES) from 1955 to 2011.

Mean Annual Runoff (MAR) volumes are listed in **Table** 4.6 for two periods: 1925 to 2021 and 1955 to 2011.

Table 4.6: Modelled and gauged Mean Annual Runoff (MAR) for the Luvuvhu and Limpopo Rivers

River	MAR ($10^6 m^3$)								
	1925 to 2021				1955 to 2011				
	Nat	PES	Fut1	Fut2 2	Hist	Nat	PES	Fut1	Fut2
Luvuvhu (floodplain)	655.8	442.3	345.7	216.6		641.9	432.2	337.9	216.1
Limpopo (confluence)[59]						2203.6	1740.6		
Limpopo (A7H004/8)[60]					2014.0				

Nat = Naturalised, Base = PES, Hist = Historical

There has been no consideration of future developments in the Limpopo River in this study since it is not part of the Scope of Work and future development scenarios were also not considered in the LIMCOM study (O'Brien *et al.* 2022). Since these data were not available there are two Limpopo River hydrological inputs into the hydrodynamic model of the Luvuvhu River floodplain, and therefore outputs from DRIFT-Luvuvhu, the Naturalised and PES flow scenarios (**Table** 4.6**)**.

The modelled Luvuvhu River flows were used in conjunction with the Beit Bridge records to 'calibrate' depth timeseries for selected pools (to the extent possible, **Section 4.2.6.1**), since there is greater certainty associated with observed than with disaggregated modelled monthly flows.

Figure 4.43 is a plot of hydrologically modelled discharge-exceedances for flood flows (*viz*. exceedance < 0.5% time) for the lower Luvuvhu River.

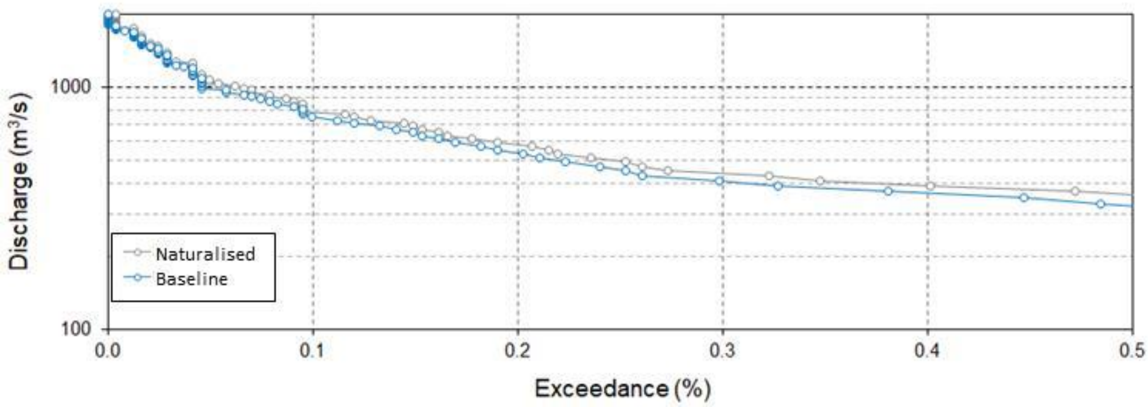

Figure 4.43: Modelled (high flow) discharge-exceedance plot for the lower Luvuvhu River (KNP) for Naturalised and PES flow scenarios

[59] excluding Luvuvhu River
[60] Beit Bridge

Hydraulic modelling (**Section 4.2.5**) indicates that flows in the range ~750 to 1 000 m^3/s are required to breach the river banks and levees in the upstream study area, and initiate widespread flooding. These flows are relatively infrequent, occurring only ~0.05 to 0.1% of the time. At these low exceedances, the reduction in discharge from Naturalised to PES flows is small (~5%); such flooding events that overtop the river's banks are not directly[61] or pragmatically manageable (e.g. through upstream reservoir releases).

4.2.6.2.2 Modelling runoff from local sub-catchments

4.2.6.2.2.1 Sub-catchment areas, rainfall timeseries and evaporation losses

Local sub-catchments that drain directly into the Makuleke wetland complex were digitally delineated using the ALOS AW3D30 global DEM[62]. Due to the low relief of the floodplain, the delineation is approximate near the pans; catchment areas used in the modelling are given in **Table** 4.7.

Table 4.7: Local sub-catchment areas for selected pans on the Luvuvhu floodplain

Pan	Catchment area (km^2)
Nwambi	2.0
Mambvumbvanyi/Reedbok	0.0
Hapi	21.3
Tlangelani	84.2

Daily rainfall records for the period 1950 to 2023 were obtained for the Pafuri Border Gate Station[63], located at the eastern boundary of the study area near the Luvuvhu-Limpopo confluence; missing observations were only 1.2% and were infilled using CHIRPS estimates. The recorded MAP from 1955 to 2011 (i.e. period of model application) was 430 mm (median 384 mm and range 105 to 927 mm); monthly rainfall is plotted in **Figure** 4.44. For comparison, the WR 2012 MAP for the relevant quaternary catchment (viz. A91K) is 376 mm[64].

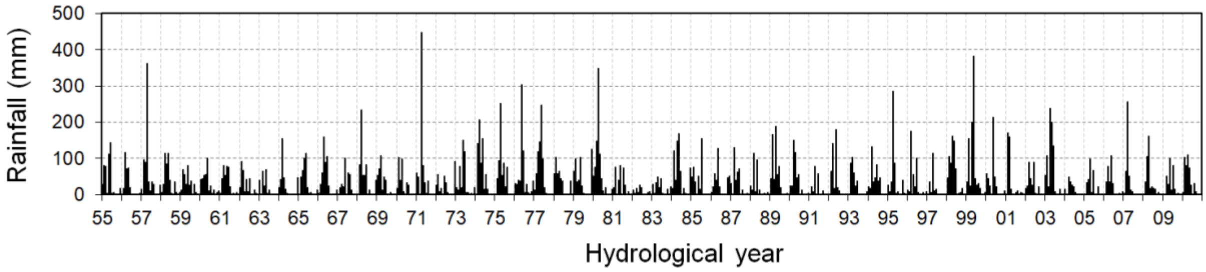

Figure 4.44: Timeseries of observed monthly total rainfall at the Pafuri Border Gate Station (1955 to 2011)

[61] i.e. excluding potential effects of climate change
[62] https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm
[63] station operated by KNP personnel
[64] likely for a longer period that pre-dates 1955

Evaporation losses, used for estimating local runoff and direct pan evaporation, was estimated using average monthly Symons(S)-pan evaporation from WR 2012 (**Table** 4.8), with an annual total of 1 845 mm (i.e. ~4 times MAP).

Table 4.8: S-pan evaporation for quaternary A91K (WR 2012)

Month	S-pan evaporation (mm)
Oct	193
Nov	185
Dec	197
Jan	192
Feb	157
Mar	157
Apr	128
May	121
Jun	99
Jul	112
Aug	137
Sep	167
Annual	1 845

4.2.6.2.2.2 GR4J rainfall-runoff model

Runoff from local sub-catchments was simulated using the daily lumped continuous rainfall-runoff model, GR4J (**Figure** 4.45**).** The model incorporates four calibration parameters (*X*1 to *X*4) as well as catchment area, daily rainfall timeseries and evaporation losses (**Table** 4.8**)**.

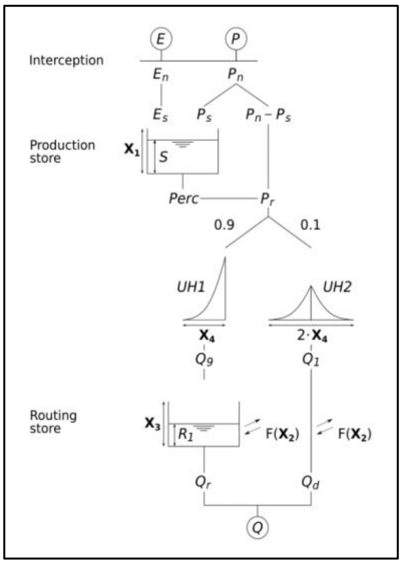

Figure 4.45: Structure of the daily GR4J rainfall-runoff model. PE: potential evapotranspiration (mm); P: rainfall totals (mm); S: level of the production reservoir (mm); UH: Unit Hydrograph; F(X2): non atmospheric exchange function; R: level of the routing reservoir (mm); Q: total streamflow (mm); X1: maximal capacity of the production reservoir (mm); X2: water exchange coefficient (mm); X3: capacity of the non-linear routing reservoir (mm); X4: unit hydrograph time base (day) (Perrin *et al.* 2003)

Runoff from local sub-catchments onto the Luvuvhu floodplain is infrequent and events are of short duration following substantial and sustained rainfall. There are no stream gauging stations nor spot discharge measurements, even for the larger sub-catchments that drain the Vlakteplaas area and discharge into pans along the southern Luvuvhu floodplain (e.g. Hapi and Tlangelani). Thus, it was necessary to estimate 'calibration' parameter values for these small basins to provide characteristic runoff regimes, which was done by the hydrologist on the study team[65]. It was also necessary to estimate the size and conveyance of the stream channels draining these catchments relative to modelled maximum flows. The parameter values adopted for the four variables ($X1$ to $X4$) in the GR4J model were 6.5; -1.5, 2.0 and 0.[66] Due to lack of streamflow data from the local sub-catchments, the four coefficients were constant for all basins.

4.2.6.3 Results and input to DRIFT-Luvuvhu

Water balances for the four EWR pan sites were computed for Naturalised, PES and two Future scenarios ('Fut1' and 'Fut2'). The hydrological characteristics of the scenarios are described in **Section 6.6**. Timeseries plots of maximum depth for the PES scenario are illustrated in **Figure** 4.46 for the period 1955 to 2011 and provide the requisite hydraulic indicators for DRIFT-Luvuvhu. For the Hapi and Thlangelani Pans located along the southern Luvuvhu floodplain, timeseries that exclude runoff contributions from the local sub-catchments were also plotted. Comparative plots for these pans indicate the high relative contribution from localised runoff from the Vlakteplaas area south of the Luvuvhu floodplain.[67]

The return periods for filing selected pans through overtopping of the Luvuvhu and Limpopo River banks are given in **Table** 4.9 for the Naturalised, PES and Future scenarios – i.e. these exclude contributions through localised runoff from ephemeral tributaries and direct rainfall. The 'return period', also known as a recurrence interval or repeat interval, is the average time between events – in this case, breaching of river levees to fill floodplain pans.

Table 4.9: Return periods for filling pans through only overtopping of the Luvuvhu/Limpopo River banks

Pan	Return period for flooding from Luvuvhu/Limpopo Rivers (years)											
	Natural			PES			Future1			Future2		
	I[68]	B[68]	O	I	B	O	I	B	O	I	B	O
Luvuvhu Floodplain												
Nwambi	7.0	2.8	2.8	7.0	4.7	4.7	9.3	5.1	5.1	18.7	7.0	7.0
Mambvumbvanyi/Reedbok	7.0	2.8	2.8	7.0	4.7	4.7	9.3	5.1	5.1	18.7	7.0	7.0
Hapi	9.3		9.3	18.7		18.7	18.7		18.7	56.0		56.0
Tlangelani	6.2	11.2	5.1	6.2	14.0	5.6	7.0	14.0	6.2	14.0	14.0	9.3

I = Inflow, B = Backfill, O = Overall

[65] Gerald Howard

[66] Applied to all local sub-catchments, given no calibration data

[67] Localised runoff from the Vlakteplaas area contributed substantially to (initial) flooding along the southern floodplain during the 2013 floods, as was (delayed) backup effect of the Limpopo (Sandra Visagie (former section section ranger, Pafuri, KNP), pers. comm.)

[68] 'inflow' refers to flow into the pan from upstream, whereas 'backfilling' denotes flow entering the pan from downstream by overtopping of the pan's invert level

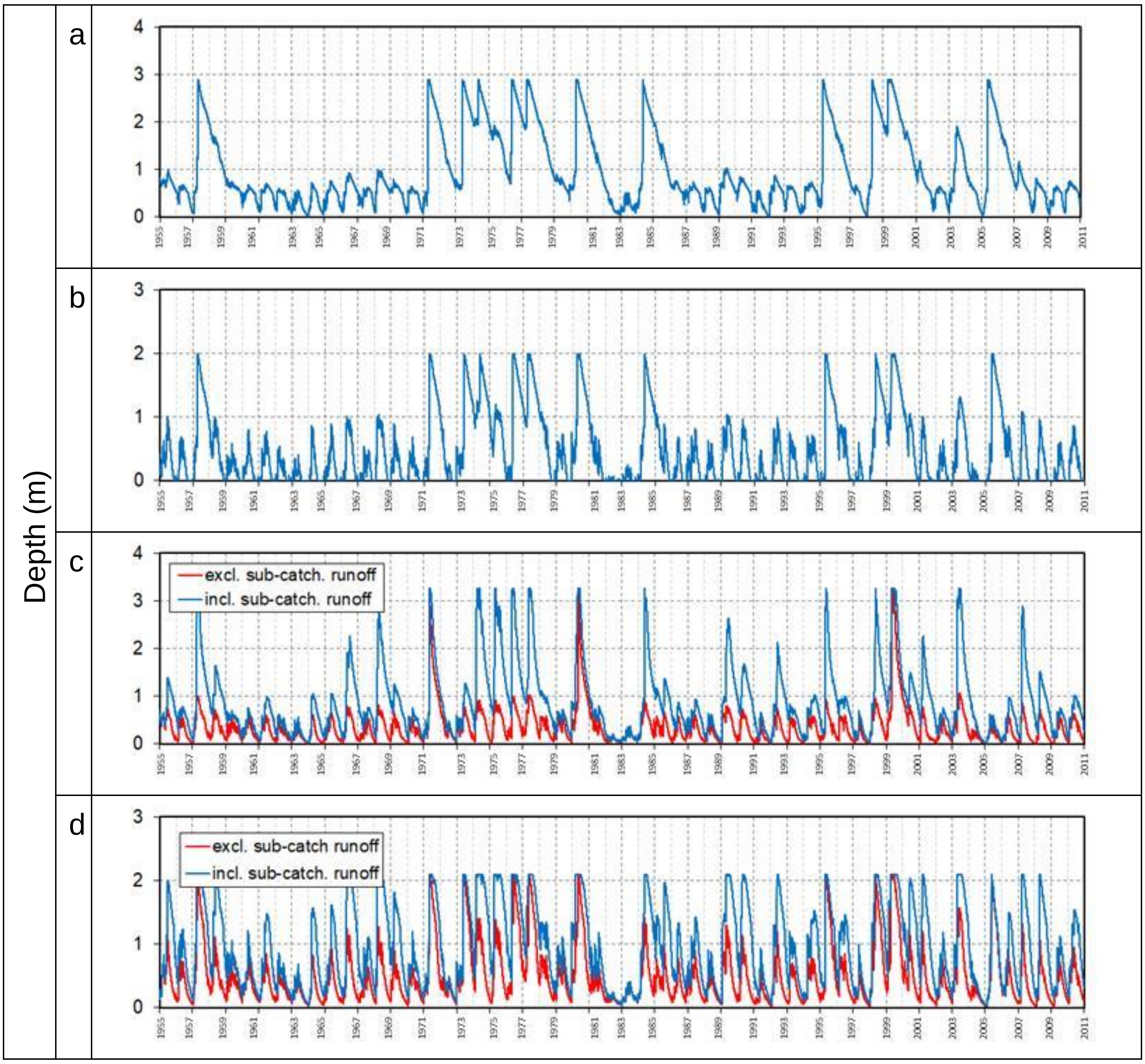

Figure 4.46: Modelled PES depth timeseries from 1955 to 2011: a) Nwambi, b) Mambvumbvanyi/Reedbok, c) Hapi, d) Tlangelani

For the Hapi Pan, including localised runoff and direct rainfall reduces the return periods from 9.3 to 4.7 years (Naturalised) and 18.7 to 4.3 years (PES). Similarly, for Tlangelani, localised runoff reduces the return period to 2.4 years (Naturalised and PES). These values are substantially closer to those calculated for Nwambi and Mambvumbvanyi/Reedbok (2.8 and 4.7 years for Naturalised and PES, respectively) - although the modes of filling are different. Under PES Tlangelani is the pan that is topped-up most frequently, through localised runoff (**Figure** 4.46**d**). Available aerial imagery (**Figure** 4.41 and **Figure** 4.42**)** indicates that it is seldom dry. The depth timeseries plots illustrated in **Figure** 4.46 (and used in the DRIFT-Luvuvhu) are derived from water balances and thus integrate all (significant) water inputs and outputs.

The Future1 scenario results in slight increases in return period (i.e. pans fills less by bank overtopping events) for Nwambi and Mambvumbvanyi/Reedbok (4.7 to 5.1 years) and for Tlangelani (5.6 to 6.2 years). The Future2 scenario is more severe in terms of a reduced Luvuvhu River flooding regime, and further increases the return period to 7.0 years (northern pans) and 9.3 years for Tlangelani. For the

Hapi Pan, levee breaching only occurs once (year 2000) in the 56-year modelled period. This, however, excludes runoff from local sub-catchments, which contributes substantially to inflows for the southern pans (Hapi and Tlangelani), as illustrated in **Figure** 4.46**.**

As discussed previously, there is a general lack of quantitative long-term hydraulic and hydrological data for the Makuleke wetland complex. Thus, it has been necessary to model characteristic behaviour, supported where possible, by available data and conceptual understanding. The analysis has, importantly, elucidated the main drivers of floodplain and pan hydrodynamics, and thus provides a better assessment of likely changes under potential future scenarios.

5 NYL RIVER FLOODPLAIN EWR

5.1 Introduction

The Nyl River floodplain is recognized internationally as an important ecological site and conservation area that supports breeding populations of inland water birds and a variety of mammals, reptiles, fish and insects (Tarboton 1987). The ecological functioning of the floodplain is driven by floods that occur in summer every three to five years (Higgins *et al*. 1996).

Nylsvley Nature Reserve is a well-known birding destination called the Nyl River floodplain IBA (IBA 2015). Three hundred and seventy species of birds, of which 102 are waterfowl, occur on the floodplain. The endangered Roan antelope (*Hippotragus equinus*) and rare Tsessebe (*Damaliscus lunatus*) also live in the reserve. The central portion of the floodplain, Nylsvley Nature Reserve was declared a Ramsar site in 1998, but the floodplain extends well beyond the boundaries of the RAMSAR site, both upstream and downstream.

Of the 102 waterfowl, 58 breed on the floodplain, more than on any other South African wetland. Twenty-three of the waterfowl are Red Data listed (Brooke 1984) and eight are resident breeders (Tarboton 1991). The Red Data listed waterfowl species breeding on the floodplain include Rufous bellied heron (*Butroides rufiventris*), Little bittern (*Ixobrychus minutus*), Dwarf bittern (*Ixobychus sturmiz*), Bittern (*Botaurus stellaris*), Pygmy goose (*Nettapus auritus*), Baillon's crake (*Porzana pusilla*), Striped crake (*Aenigmatolimnas marginalis*) and Black stork (*Ciconia nigra*). The Streaky breasted flufftail is an endemic resident. During good rainy seasons, the floodplain becomes a hype of activity. The best estimate for water bird numbers on the floodplain during floods is ~80 000 (Tarboton 1987). The floodplain is also the only location in South Africa where wild rice (*Oryza longistaminata)* grows (Gibbs Russell *et al*. 1991) and is an important breeding ground for frogs and toads after rain and during floods. Fish move onto the floodplain during floods to breed, biomass estimates currently are 300 - 600 tons, depending on the extent of flooding.

The floodplain is in a basin on the downstream side of a fault and is a low-gradient fluvial landform where flooding occurs mainly as sheetflow (Tooth *et al.* 2002). At the downstream end bedrock outcrops converge to form the Mogalakwena River.

The floodplain receives water and sediment on a seasonal basis from the Nyl River and its tributaries (Tooth *et al*. 2002). The Olifantspruit River, on which river EWR Site 3_Olifantspruit is located (River Assessment (Volume3): Ecological Water Requirements Report) is one such tributary.

The ecological functioning of the floodplain is linked to the spatial and temporal variability of the flooding regime (Higgins *et al*. 1997), which has decreased in frequency and duration due to agricultural and urban water use (Higgins and Rogers 1993; Higgins *et al*. 1996) and due to high variation in rainfall; channel flows occur in seven out of ten years and the floodplain is inundated in four out of ten years (Higgins *et al*. 1997).

The flooding regime is a primary determinant of plant species distribution, but soil type is also a major secondary influence (Coetzee and Rogers 1991). The six landforms with different flooding regimes are the channel, oxbows, the floodplain, sodic areas, floodplain-sodic site ecotones and back-flooded areas (Higgins *et al*. 1997).

5.2 EWR zones

The Nyl River floodplain was divided into three zones (**Figure** 5-1):

- 15_Nylsvley 1[69] – upstream of Nylsvley Nature Reserve.
- 16_ Nylsvley 2 –Nylsvley Nature Reserve.
- 17_Nylsvley 3 – downstream of Nylsvley Nature Reserve.

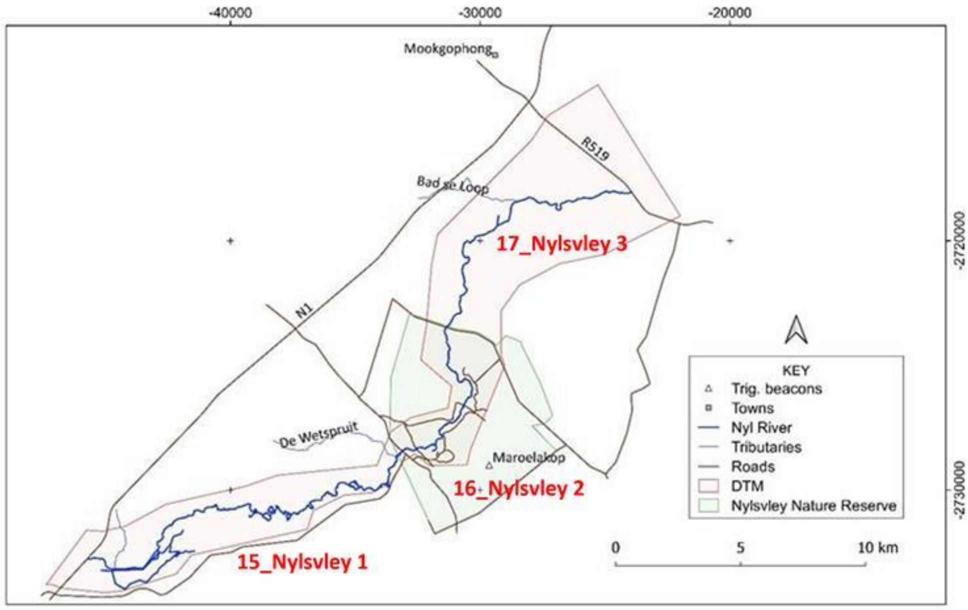

Figure 5-1: The 3 EWR zones at the Nyl River floodplain

5.2.1 15_Nylsvley1

15_Nylsvley1 is ~22-km long and ~ 2-km wide. This zone comprises a grass and sedge floodplain with a defined channel and backwater pools **(Figure** 5-2). Some of the channel is straightened and some areas of the floodplain are cleared, tilled, or drained for farming (**Figure** 5-3**)**. Landuse includes commercial annuals crops (with or without pivot irrigation), open woodland (10 - 35%), natural grassland, herbaceous wetlands and fallow land. Most of the area is used for agriculture, grazing or wildlife farming. The floodplain constricts towards the lower end of this zone and flows through road culverts into 16_Nylsvley2.

5.2.2 16_Nylsvley2

16_Nylsvley2 is ~8-km long and varies from 500 m to 3.8 km in width. This zone comprises a grass and sedge dominated floodplain with a defined channel and backwater pools with dense reed beds (**Figure** 5-4**)**. Where the floodplain widens there are more-or-less circular clumps of shrubs on raised mounds (due to interaction with groundwater) that have a different inundation regime. Some of the channel's course is altered and dammed to create bird hides (**Figure** 5-5**)**. Landuse includes herbaceous wetlands, open woodland (10 - 35%) and natural grassland. There are few exotics plants because the area is

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[69] The numbering of the wetland EWR sites is a continuation of that used for the 14 rivers EWR sites (River Assessment (Volume2): Ecological Water Requirements Report).

cleared regularly. The floodplain widens towards the end of this zone and passes through several road culverts into 17_Nylsvley3.

Figure 5-2: 15_Nylsvley1 (January 2023) showing a grass and sedge floodplain (left) and a channel and backwater (right)

Figure 5-3: Satellite image (Bing) of 15_Nylsvley1 showing channel straightening

5.2.3 17_Nylsvley3

17_Nylsvley3 is ~9.5-km long and ~3.8-km wide. This zone comprises a grass and sedge floodplain with an ill-defined channel and scattered trees and shrubs (**Figure** 5-6). The channel has been straightened and infilled, many areas are cleared, tilled and drained for agriculture (**Figure** 5-7). Landuse is commercial annuals crops, natural grassland, open woodland (10 - 35%), herbaceous wetlands and dense forest/woodland (35 - 75%). There are agricultural fields, grazing fields and wildlife farms.

Figure 5-4: 16_Nylsvley2 (January 2023) showing a grass and sedge floodplain (left) and a channel with backwaters

Figure 5-5: Satellite image (Bing) of 16_Nylsvley2 showing two distinct grassland types and reeds associated with pools (this one with a bird hide)

Figure 5-6: 17_Nylsvley3 (January 2023) showing a grass and sedge floodplain lacking a well-defined channel (left) and scattered trees and shrubs (right)

Figure 5-7: Satellite image (Bing) of 17_Nylsvley3 showing channel manipulation

5.3 Hydrodynamic indicators

DRIFT-Nylsvley used modelled areas, depths and durations of inundation as the main (driving) input data.

All the time-series use the same period: 1925-2021. Once imported into DRIFT-Nylsvley, the time-series were summarized into ecologically relevant 'driver' indicators, reported as annual values or as values for one or more of four hydrobiological flow seasons (**Section 2.2.3**):

- Dry Season (Dry)
- Transition Season 1 (T1)

- Flood/Wet Season (Flood)
- Transition Season 2 (T2).

The indicators created using these time-series' and the seasons for which they were calculated are provided in **Table** 5.1.

Table 5.1: DRIFT-Nylsvley hydrodynamic input data and indicators

Discipline	Season	Indicator	Units
Hydrodynamics	Annual	Mean annual area	km^2
		Zero flow days per year	days
		Duration emergent grass	
		Duration central floodplain grass	
		Duration edge floodplain grass	
		Duration shrubs and trees	
		Frequency central floodplain grass	
		Frequency edge floodplain grass	
	Dry Season	Onset	calendar week
		Duration	days
		Minimum 5-day area	km^2
		Average maximum depth aquatic grass	m
		Average maximum depth central floodplain grass	
		Average maximum depth edge floodplain grass	
	Flood/Wet Season	Onset	calendar week
		Duration	days
		Maximum 5-day area	km^2
		Average maximum depth aquatic grass	m
		Average maximum depth central floodplain grass	
		Average maximum depth edge floodplain grass	
		Area emergent grass	km^2
		Area central floodplain grass	
		Area edge floodplain grass	

5.4 Indicators

A list of wetland indicators and reasons for their selection are listed in **Table** 5.2.

Table 5.2: Wetland indicators and reasons for their selection

Indicator	Reason for selection	EWR zone 15	EWR zone 16	EWR zone 17
Aquatic vegetation	Aquatic plants are important as food for many animals and provide habitat for aquatic organisms, and some improve water quality. They also have medicinal and food value for humans.	X	X	X
Reeds	Reeds are eaten by domestic and wild herbivores and provide important habitat for aquatic invertebrates.	X	X	X
Central floodplain grass (wet)	Central floodplain grasses are an important source of food for birds and mammals and as breeding grounds for birds, fish, amphibians and mammals. They are also grazing areas for domestic livestock and play a role in flood attenuation and erosion control.	X	X	X
Edge floodplain grass (dry)	Edge floodplain grasses are important grazing areas for wildlife and domestic livestock. They provide habitat for wildlife when the central floodplain grasses are inundated. They play a role in flood attenuation and erosion control.	X	X	X
Shrubs and trees	Shrubs and trees grow on the edges of the floodplain or on raised mounds and are important habitat for a variety of floodplain animals.	X	X	X
Coenogrionidae	Coenogrionids inhabit marginal vegetation in slow flowing water and are an important food source for birds and fish.	X	X	X
White-breasted cormorant	White-breasted cormorants feed on fish in open water (pools, pans, backwaters and the channel). They were selected to represent all birds that feed in open water because they are very abundant at Nylsvley.	X	X	X
White-faced duck	White-faced ducks spend time on open water and in marginal vegetation, are omnivorous eating seeds, tubers and invertebrates (insects, crustaceans and worms). They were selected to represent all dabbling waterfowl (ducks and teals) because they were very abundant at Nylsvley.	X	X	X
Water buck	Waterbuck inhabit grasslands and are highly dependent on water to maintain their hydration. They also favour reeds as one of their food items. They were selected because they are one of the flagship water-dependent antelope at Nylsvley.	X	X	X
Floodplain dependent fish	Floodplain dependent fish move onto the floodplains to breed and the inundated floodplains provide nursery areas for juvenile fish.	X	X	X

5.4.1 Aquatic vegetation

Aquatic plants grow rooted into the bed of pools, lakes or backwaters and with leaves beneath the surface of the water or that grow up and open at the water surface. Oxygen Weed, *Lagarosiphon ilicifolius,* represents this guild, which grows rooted into the channel bed submerged beneath the surface. It grows in the backwaters on the floodplain (Ellenbroek 1987) and provides important habitat for aquatic insects (Phiri *et al*. 2012).

The oxygen weed (**Figure** 5-8) is an aquatic perennial plant that grows beneath the surface of the water and comprises soft green stems with short fleshy green leaves that whorl up the stem. The plant grows with multiple branches from a rooted base and occurs as a free-floating plant if stems become detached. Oxygen weed is a perennial plant, the main growing season is summer (October to February) with extensive branching that takes place, which blocks light to the rooted stems that then break off and create fragment mats that float away (Machena *et al*. 1990). These floating plant fragments are able to take root and grow into new plants if they are deposited on a suitable substrate (Phiri *et al*. 2012).

Figure 5-8: Aquatic plants – *Lagarosiphon illicifolium*

Oxygen weed provides habitat, protection from predators, and food in the form of trapped particulate organic matter for many aquatic insects (Phiri *et al*. 2012). It also provides cover from predation for many fish (Machena *et al*. 1990) and amphibians. Waterbirds, especially ducks, eat the Oxygen weed. The plant can grow in a variety of conditions, from very shallow to deep water, and in many sediment types. Oxygen weed grows well when there is an excess of nutrients (www.wikipedia.com). Like most aquatic plants, it prefers still or slow-moving water and is uprooted or broken apart when flow velocities increase (www.cabi.org).

The linked indicators, reasons for their selection and their relationship with aquatic vegetation are summarised in **Table** 5.3.

Table 5.3: Linked indicators and their relationship with aquatic vegetation.

Linked indicator	Reasons	Relationship
Dry min 5d area	Rooted aquatics survive the dry season rooted in open water (Machena et al.1990) of depths ⩽2.0 m (www.tropics.com). No growth takes place (Machena et al.1990) and the roots will perish if dried out.	More water in the dry season = more aquatic vegetation.
Wet duration	Aquatic plants are adapted to permanent life in the water, and some are able to endure dormancy. Rooted aquatics flourish in the wet season (Moreau 1997). A shortened duration of the wet season may result in desiccation if pools drop too low or dry out. Those species not able to undergo dormancy will die.	Longer wet seasons = more aquatic vegetation.
Zero days per year	An increase in the number of days with zero flow equates to an extended dry season, which, if too long may result in desiccation stress or death, or trigger dormancy.	Fewer zero days = more aquatic vegetation.
Dry season: average max depth	Aquatic plants prefer to grow in still to slow flowing water at depths from 0.5 to 1.5 m. (van Ginkel and Cilliers 2017). Shallower water heats up and become intolerable.	Shallow water = fewer aquatic plants.
Wet season: average max depth		

5.4.2 Reeds

Phragmites australis is a perennial reed that grows up to 4 m in height with long rhizomes that flower from December to June (**Figure** 5-9). When conditions are favourable, *P. australis* can form stands up to 1 km^2 and can grow laterally at a rate of ~5 m per year. It grows in damp ground and in standing water up to 1 m deep, and even as a floating mat. It tolerates brackish water and can be invasive if not supressed by grazing, burning or floods. It grows in all moist soil types. It plays an important role in protecting soil from flooding and in filtering water (Plantzafrica.com). *P. australis* provides food and habitat for birds and aquatic reptiles (Milke *et al*. 2020).

The linked indicators, reasons for their selection and their relationship with reeds are summarised in **Table** 5.4.

Table 5.4: Linked indicators and their relationship with reeds.

Linked indicator	Reasons	Relationship
Wet onset	Reeds are dormant in the dry season and start to grow in late spring (October). If the plants are inundated during dormancy the roots may rot.	Early onset of the wet season = fewer reeds.
Wet duration	Reeds grow during the wet season. Wet season duration should be >3 months, and longer wet seasons will promote extended growth and expansion of reeds. A wet season <3 months is likely to result in desiccation or early dormancy.	A longer wet season = more reeds.
Wet area emergent vegetation	Reeds grow and reproduce in the wet season. The greater area flooded the more reeds will grow and spread.	More flooded area = more reeds.
Duration emergent vegetation	Reeds starts to grow when inundated in Spring and Summer.	Periods of longer inundation = more reeds.

5.4.3 Central floodplain grasses (wet)

Rice grass (*Oryza longistaminata*) occurs exclusively on the Nylsvley floodplain in South Africa (Gibbs Russell *et al*. 1991) and is listed as Vulnerable at a National scale. *Oryza longistaminata* is a perennial species of grass (**Figure** 5-10) from the same genus as cultivated rice (*O. sativa*). This species grows in full sunlight and is found in swampy areas, at the edges of lakes or ponds, and grows in water up to 4 m deep, but usually in ⩽1 m (Vaughan 1994). It does not seem to reproduce sexually on the Nylsvley floodplain, which makes preservation of the rhizomes vital for its continued existence (Gary Marneweck pers. comm. 2023). This is achieved by the preferred flooding regime for Rice grass, which consists of a flood at least every 3 years and optimally for 150 days at depths varying from 0.1 – 0.5 m or more (Gary Marneweck pers. comm. 2023). It provides important seasonal food reserves for granivorous birds and is also grazed.

The linked indicators, reasons for selection and their relationships with central floodplain grasses are summarised in **Table** 5.5.

Table 5.5: Linked indicators and their relationship with Central floodplain grasses.

Linked indicator	Reasons	Relationship
Dry onset	*Oryza longistaminata* is dormant in July and August and its life cycle must be completed before the onset of winter to nourish the rhizomes for the next flood response (Marneweck pers. comm. 2023).	Early onset of the dry season = less central floodplain grasses.
Wet onset	Wet season onset should ideally take place in November and a good growing season will last up to March. Early onset will inundate dormant rhizomes causing root rot. Delayed onset will shorten the growing season and create the risk that central floodplain grasses will not complete their life cycle (Marneweck pers. comm. 2023).	Early and delayed onset of the wet season = fewer central floodplain grasses.
Wet area central floodplain grass	Central floodplain grasses grow best at the inundation depth of ~ 0.1 to 0.5 m.	More area inundated at the correct depth = more central floodplain grasses.
Duration of inundation of central floodplain grass	Rhizomes respond to being inundated and first grow new rhizomes (30 – 45 days) before allocating resources to new stolons to complete its life cycle in ~ 150 days (optimum flooding duration, Marneweck pers. comm. 2023).	A shorter duration of inundation = less central floodplain grasses.
Flooding frequency of central floodplain grass	The ideal flooding frequency is 2 floods every 5 years (Marneweck pers. comm. 2023). Primary production is optimal during years in which flooding occurs.	Less frequent floods = fewer central floodplain grasses.
Wet average maximum depth	Oryza does best at inundation depths of 0.1 to 0.5 m (Marneweck pers. comm. 2023) and also benefits from extended inundation at shallow depths of 0.25 m. Inundation at a deeper depth of 0.75 m uses up more energy for stolons to reach the water surface at the expense of energy that could be allocated to storage in the rhizomes (Marneweck pers. comm. 2023).	Deeper water depth in the wet season = fewer central floodplain grasses.
Shrubs and trees	Shrubs and trees compete with floodplain grasses for resources and are usually favoured at the expense of floodplain grasses when the flooding regime is altered / reduced i.e. drier periods with less flooding frequency and shorter inundation durations.	More shrubs and trees = fewer central floodplain grasses.

Figure 5-9: Reeds – arrows show *Phragmites australis* at Nylsvley Nature Reserve

Figure 5-10: *Oryza longistaminata* at Nylsvley in January 2023, inset shows an inflorescence

5.4.4 Edge floodplain grasses (dry)

Dry floodplain grasses grow on the outer edge of the floodplain that is inundated to a lesser extent and for a shorter duration. The dynamics of the edge floodplain is similar to that described for the central floodplain areas with there being a variety of graminoids that respond in different ways to grazing, fire, inundation and trampling that creates a mosaic of different species at different times of the year and between years. Swamp rice grass, *Leersia hexandra* (**Figure** 5-11), has been selected to represent this guild that is less regularly inundated and provides good grazing for livestock and antelope. These higher lying areas are refugia for animals and birds during wet periods (Ellenbroek 1987).

Figure 5-11: Swamp rice grass, *Leersia hexandra* at Nylsvley in January 2023

Swamp rice grass is a semi-aquatic, non-tufted, spreading, perennial grass with a distinct creeping spongy stem and erect stems up to 1 m in height. The plant flowers all year round (Ellery and Ellery 1997). Swamp rice grass grows in a variety of wet and seasonally inundated habitats often forming extensive colonies (Gibbs Russel *et al.* 1990). The seeds are eaten by ducks and teals, and it is regarded as a good grazing grass, especially in winter when the environment is drier, and the grass is more accessible (van Ginkel and Cilliers 2017). The extended rhizome system provides protection against erosion during floods.

The linked indicators, reasons for selection and their relationships with edge floodplain grasses are summarised in **Table** 5.6.

Table 5.6: Linked indicators and their relationship with edge floodplain grass

Linked indicator	Reasons	Relationship
Wet onset	*Leersia hexandra* is dormant in the dry season and starts to grow in spring. If the rhizomes are inundated when dormant they will rot. The ideal timing of onset of the wet season is October.	Early onset of the wet season = fewer edge floodplain grasses.
Wet duration	A wet season shorter than 3 months is likely to cause desiccation or early dormancy.	A wet season longer = more edge floodplain grasses.
Wet area edge floodplain grass	Edge floodplain grasses grow best when inundated at depths of up to 0.1 m.	More wet area at the correct depth = more edge floodplain grasses.
Duration of inundation edge floodplain grass	The longer edge floodplain grasses are inundated at the correct depth the longer their growing season.	A longer duration of inundation = more edge floodplain grasses.
Frequency of flooding	Flooding frequency of at least 2 in every 5 years is required.	Less frequent floods = fewer edge floodplain grasses.
Wet average maximum depth edge floodplain grass	Edge floodplain grasses will not grow if the depth of inundation exceeds 30 cm.	Greater depths of inundation = fewer edge floodplain grasses.
Shrubs and trees	Shrubs and trees compete with floodplain grasses for resources and are usually favoured at the expense of floodplain grasses when the flooding regime is altered / reduced i.e. drier periods with less flooding frequency and shorter inundation durations.	More shrubs and trees = fewer edge floodplain grasses.

5.4.5 Shrubs and trees

Shrubs and trees grow at various places on the floodplain in circular clumps around raised mounds that are likely linked to groundwater supply (Tooth et. al. 2002). The main species are *Searsia pyroides, Diospyros lyceoides, Ziziphus mucronata* and *Vachellai karroo* (**Figure** 5-12). This indicator represents terrestrial vegetation that may encroach upon the floodplain during drier periods.

Figure 5-12: Shrub and tree clumps on the floodplain showing *Ziziphus mucronata* in the foreground at Nylsvley in January 2023

The linked indicators, reasons for selection and their relationships with shrubs and trees are summarised in **Table** 5.7**.**

Table 5.7: Linked indicators and their relationship with shrubs and trees

Linked indicator	Reasons	Relationship
Wet duration	Shrubs and trees are terrestrial, and longer periods of inundation prevent them from encroaching onto the floodplain.	Longer wet duration = fewer shrubs and trees.
Wet area shrubs and trees	Shrubs and trees are terrestrial and grow on the elevated mounds and the dry edges of the floodplain.	The more floodplain inundates the less shrubs and trees will occur on the floodplain.
Duration of inundation shrubs and trees	Shrubs and trees are terrestrial so do not grown well if inundated for too long.	A longer duration of inundation = fewer shrubs and trees.

5.4.6 Coenagrionidae

Coenagrionids (**Figure** 5-13**)** are damselflies whose larvae climb through and stalk invertebrate prey among plants and roots (Macroinvertebrates, accessed on 14 September 2023). Coenagrionids prefer well-lit, weedy margins of river pools (Samways *et al*. 1996). Coenagrionids prefer standing water (< 0.1 m/s) and can tolerate poor water quality (Thirion 2016). Most coenagrionids are univoltine, a few are bivoltine, and others are multivoltine (Phiri *et al*. 2012). Adults emerge from spring to autumn; the females lay eggs on aquatic vegetation beneath the surface of the water. Some species produce eggs that can over-winter with eggs being laid in autumn and larvae emerging in spring (Centre for Freshwater Biology, accessed on 14 September 2023).

Figure 5-13: A coenagrionid (Gerber & Gabriel, 2002)

The linked indicators, reasons for selection and their relationships with Coenagrionids are summarised in **Table** 5.8**.**

Table 5.8: Linked indicators and their relationship with Ceonagrionids

Linked indicator	Reasons	Relationship
Aquatic vegetation (All seasons)	Coenagrionidae inhabit aquatic vegetation (Thirion 2016).	More aquatic vegetation = more coenagrionids.

5.4.7 White-breasted Cormorant

White-breasted cormorants (*Phalacrocorax lucidus*) occur singly or in groups on coastal rocks, islands and estuaries as well as large inland waterbodies where they often perch in dead trees (South Africa Online: https://southafrica.co.za/whitebreasted-cormorant.html; **Figure** 5-14). The white-breasted cormorant breeds throughout the year in South Africa with peak periods in March to October. The nest is a flat platform of sticks, twigs and feathers. The white-breasted cormorant eats fish and swims under water to catch its prey. The jaw is adapted to catch slow moving bottom-dwelling fish, but it may also catch faster fish at the surface. Smaller fish are swallowed underwater, but larger fish are taken to shore. On the Nylsvley floodplain they catch fish in open water and on the floodplain when inundated.

The linked indicators, reasons for selection and their relationships with white-breasted cormorants are summarised in **Table** 5.9.

Table 5.9: Linked indicators and their relationship with White-breasted Cormorants

Linked indicator	Reasons	Relationship
Wet duration	White-breasted cormorants hunt in the shallow and deep water during the wet season, when there is more water in which to hunt (https://www.oiseaux-birds.com/card-reed-cormorant.html). More hunting grounds provide more food for adults and chicks.	A longer wet season = more white-breasted cormorants.
Zero days per year	Cormorants remain on permanent water bodies so if there are no open water habitats the birds will move elsewhere to hunt (https://www.oiseaux-birds.com/card-reed-cormorant.html).	More zero days = fewer cormorants.
Reeds	Cormorants build their nests hidden in long grasses and reeds (https://www.oiseaux-birds.com/card-reed-cormorant.html).	More reeds (and associated graminoids) means more breeding and nesting habitat = more cormorants.
Shrubs and trees	Cormorants also nest in trees over water (https://www.oiseaux-birds.com/card-reed-cormorant.html).	More shrubs and trees = more breeding sites = more cormorants.
Floodplain dependent fish	Cormorants eat a variety of fish, but also do take other prey such as frogs, aquatic invertebrates and small birds (https://www.oiseaux-birds.com/card-reed-cormorant.html).	More fish = more food = more cormorants.

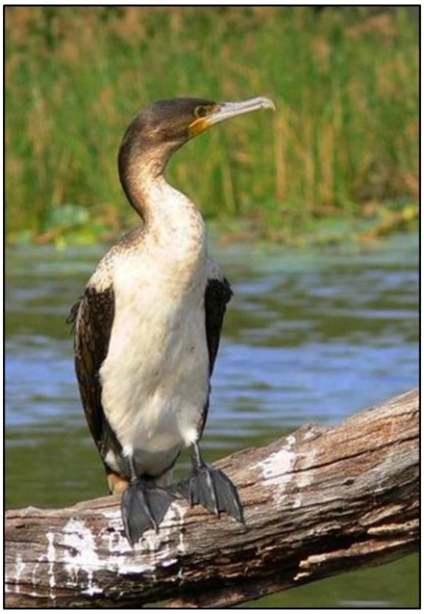

Figure 5-14: White-breasted Cormorant, *Phalacrocorax lucidus* (Photograph: Tony Faria cybeR@NGER)

5.4.8 White-faced duck

Adult males of the white-faced duck (*Dendrocygna viduata*; **Figure** 5-15) have a white half front of their head and throat and the rest is black, the wing shoulders are chestnut. The female is similar but has the front of the head and neck spot tinged with rust colour. It does not spend much time perched in trees, rather they prefer dabbling along sand banks (www.krugerpark.co.za).

The white-faced duck is omnivorous and was selected as an indicator to represent other dabbling ducks and teals that occur in backwaters and oxbows on floodplains. It is a social bird that occurs in large flocks (McLachlan and Riversidge 1978) and in large numbers on the Nylsvley floodplain when in flood (www.ramsar.org/ris). They are omnivorous and eat seeds, tubers and invertebrates (insect larvae, insects, worms and crustaceans; McLachlan and Liversidge 1978).

Mutual preening plays an important part in the formation of pairs and maintenance of bonds. Nests are built of leaves on the ground in marshes and in hollow trees (www.krugerpark.co.za) at the end of the dry season from October to November. Clutches consist of 6 to 12 eggs, and both partners incubate the eggs for 28 to 30 days. The ducklings are often hidden in aquatic vegetation by the parents (McLachlan and Riversidge 1978).

The linked indicators, reasons for selection and their relationships with white-faced ducks are summarised in **Table** 5.10.

Table 5.10: Linked indicators and their relationship with white-faced ducks

Linked indicator	Reasons	Relationship
Wet duration	White faced duck hunt in the shallow open water of rivers, lakes and wetlands (McClachlan and Liversidge 1978) which are dependent on the duration of the wet season to remain wet and deep enough.	A longer wet season = more white-faced duck.
Zero days per year	White-faced ducks live in and on permanent water bodies (McClachlan and Liversidge 1978). If the water bodies dry out the ducks will move off to other areas of permanent water.	More zero days = fewer ducks.
Aquatic vegetation	White-faced duck are omnivores eating seeds of aquatic plants, tubers, invertebrates, insects, worms and crustaceans (McLachlan and Liversidge 1978).	More aquatic vegetation = more feeding areas = more ducks.
Reeds	White-faced duck nest and hide their young in marshes (reeds and other graminoids at the water's edge) (www.krugerpark.com).	More reeds = more nesting and hiding places = more ducks.
Coenagrionids	White-faced ducks eat aquatic insects ((McLachlan and Liversidge 1978).	More insects = more ducks.

Figure 5-15: White-faced Duck, *Dendrocygna viduata* (Photograph: www.wikipedia.com)

5.4.9 Waterbuck

The waterbuck, *Kobus ellipsiprymnus*, is a large gregarious antelope that form herds of six to 30 individuals (Spinage 1982). Groups of animals may comprise nursery herds of females and young, bachelor herds and territorial males. Herd sizes increase in summer over the wet season and fragment in winter probably due to food availability (Melton 1978). This antelope acquired its vernacular name "waterbuck" due to its heavy dependence on water compared to other antelopes and its use of water to escape predators (**Figure** 5-16; Taylor *et al*. 1968).

Waterbuck are dependent on water and cannot tolerate dehydration in hot weather (Kingdon 1989). They inhabit areas close to sources of water but have been known to range into the woodlands close to water (Nowak 1999). With grasses constituting 70-95 % of their diet, waterbuck are predominantly grazers frequenting grasslands, wetlands and floodplains. Reeds and rushes like *Typha* and *Phragmites* may also be eaten (Kingdon and Hoffman unknown date).

Figure 5-16: Waterbuck (*Kobus ellipsiprymnus)* prefer grasslands near water and often enter waterbodies

The linked indicators, reasons for selection and their relationships with waterbuck are summarised in **Table** 5.11.

Table 5.11: Linked indicators and their relationship with waterbuck

Linked indicator	Reasons	Relationship
Zero days per year	Waterbuck cannot tolerate dehydration in hot weather (Taylor *et al*. 1969), and thus inhabit areas close to water. Predominantly a grazer, the waterbuck is mostly found on grassland along rivers, and near wetlands and floodplains.	More zero days per year = fewer waterbuck.
Central floodplain grasses Edge floodplain grasses	Waterbuck graze grasses on the floodplain that comprise 70-95% of their diet (www.wikipedia.com). If there are no grasses, they can eat reeds, and leaves, shoots and fruits from shrubs and trees.	More floodplain grasses = more waterbuck.
Shrubs and trees	Waterbuck eat leaves, shoots and fruit from shrubs and trees in the dry season.	More shrubs and trees = more waterbuck.

5.4.10 Floodplain dependent fish

Floodplain fish are represented by *Enteromius trimaculatus*, the threespot barb (**Figure** 5-17**)**.

 

Figure 5-17: *Enteromuis trimaculatus* (Photographs: Mathew Ross)

They prefer and inhabit quiet vegetated waters on the edges of the river or in backwaters and on floodplains. It is a hardy species that commonly occurs in a wide variety of habitats, especially where there is vegetation. It feeds on insects and other small organisms. They breed in summer, shoals of ripe adults move upstream or onto the floodplain after rain. Females produce as many as 8000 eggs (Skelton 2001).

The linked indicators, reasons for selection and their relationships with floodplain dependent fish are summarised in **Table** 5.12.

Table 5.12: Linked indicators and their relationship with floodplain dependent fish

Linked indicator	Reasons	Relationship
Zero days per year	Fish and invertebrates are concentrated in standing pools on zero flow days, which increases competition for resources.	More zero flow days = fewer three-spot barb.
Wet area central floodplain grass	Three-spot barb breed and feed in central floodplain grasses during floods in the wet season (Skelton 2001). The larger area of central floodplain grasses inundated and the longer the more successful breeding will be.	More and longer inundated central floodplain grasses = more three-spot barbs.
Duration of inundation central floodplain grass		
Aquatic vegetation	Three-spot barb breed and feed in aquatic vegetation (Skelton 2001).	More aquatic vegetation = more three-spot barbs.
Coenagrionidae	Three-spot barb eat invertebrates (Skelton 2001).	More invertebrates = more three-spot barb.

5.5 Present Ecological Status (PES)

The Present Ecological Status (PES) of the Nyl River floodplain was determined using the WET-Health Level 1 (Macfarlane *et al*. 2007) assessment method that generates an Ecological Category for Hydrology, Geomorphology, Water quality and Vegetation for the whole floodplain. The Nyl River floodplain was modelled as three zones in DRIFT-Nylsvley (Section 5.2) so a higher score than that generated by the WET-Health model was assigned to the Ramsar site 16_Nylsvley2 because it is in a better overall condition than the two other zones of floodplain situated outside of the Nylsvley Nature Reserve. The PES for the biota was derived from a combination of two or three of the floodplain driver scores (as appropriate) and adjusted based on other available information (local knowledge, literature, data) and observations in the field if necessary. The vegetation module score was 58%, a C/D category

(Wetland Assessment Volume 1 – Ecostatus and Priority Wetlands.). The rating, reasons and results are shown in **Table** 5.13.

Table 5.13: Vegetation module (WetHealth Level 1; Macfarlane *et al*. 2007) for the Nyl River floodplain

Disturbance Class	Extent (%)	Typical intensity	Intensity (0 - 10)	Magnitude	Additional Notes	Confidence rating
Infrastructure	0.05	10	10	0.0	Calculated from NLC 2020	High
Deep flooding by dams	0.12	10	10	0.0		
Shallow flooding by dams	2	4 - 8	8	0.2		
Crop lands	15.36	8 - 10	10	1.5		
Commercial plantations	0.01	7 - 10	10	0.0		
Annual pastures	5	9 -10	9	0.5		
Perennial pastures	10	4 -10	8	0.8		
Dense alien vegetation patches.	5	5 - 10	10	0.5		
Sports fields	0	7 - 10	9	0.0		
Gardens	0.06	6 - 10	8	0.0		
Areas of sediment deposition/ infilling and excavation	3	4-10	8	0.2		
Eroded areas	0.05	3 - 9	8	0.0		
Old/abandoned lands (Recent)	2	7 - 9	7	0.1		
Old/abandoned lands (Old)	2	3 - 8	5	0.1		
Seepage below dams	0.5	1 - 5	7	0.0		
Untransformed areas	5	0 - 3	4	0.2		
Overall weighted impact score				4.2		
Vegetation PES% Score				58 %		
Vegetation PES Category				**C/D**		

The overall PES for the Nyl River floodplain is 65%, a C category (**Table** 5.14). The primary drivers of change are agricultural activities within the floodplain, floodplain disturbance including berms for water retention, channel re-routing and canalisation, and an altered flow regime. In DRIFT-Nylsvley, the ecological categories of 15_Nylsvley1 and 17_Nylsvley3 were given the C category and the Ramsar site 16_Nylsvley2 a half category higher to a B/C category.

Table 5.14: Overall PES for the Nyl River floodplain

Components	Method used for assessment	PES% Score	Ecological Category
Hydrology PES	WET-Health Hydrology Module	65 %	C
Geomorphology PES	WET-Health Geomorphology Module	73 %	C
Water quality PES	Wetland-IHI Water Quality Module	79 %	B/C
Vegetation PES	WET-Health Vegetation Module	58 %	C/D
Overall Wetland PES	WET-Health default weightings	**65 %**	**C**

Combining the categories for hydrology and water quality resulted in a B/C category for invertebrates that was raised by half a category to a B because of the high diversity of Odonates at Nylsvley Nature

Reserve (https://nylsvley.co.za/info-on-nylsvley/) (**Table** 5.15**)**. Coenagrionids are damselflies that prefer well-lit vegetated pools (Samways *et al*. 1996). They thrive on the Nyl River floodplain when flooded. The adults are active flyers and move around to find suitable habitat in which to breed.

Combining the categories for hydrology, water quality and geomorphology for fish resulted in a C category (**Table** 5.15). Floodplain dependent fish are transient and depend on the flooding regime to grow and recruit and backwater refugia to persist through the dry season. Floodplain dependent fish thrive in large numbers on the Nyl River floodplain during floods, but fish movements are somewhat restricted because of the culverts where fish are caught when migrating.

Combined categories for hydrology, water quality and vegetation for white-faced duck and white-breasted cormorants resulted in a C category that was raised by half a category to a B/C category (**Table** 5.15) because Nylsvley Nature Reserve was designated Ramsar status largely due to the diversity and abundance of waterbirds. The other two neighbouring protected areas, Deelkraal upstream and Sandfields and Forests downstream, also provide good quality habitat and protection for waterbirds.

Combined categories for hydrology, water quality and vegetation for mammals resulted in a C category that was raised by half a category to a B/C category (**Table** 5.15**)** because of the protection status and good quality habitats in Nylsvley Nature Reserve, Deelkraal, Sandfield and Forests.

Table 5.15: Derived scores for biota on the Nyl River floodplain

<table>
<tr><th>Discipline</th><th>Indicator in DRIFT</th><th>WET-Health drivers combined</th><th colspan="2">Ecological category</th></tr>
<tr><td>Invertebrates</td><td>Coenagrionids</td><td>Hydrology (C), water quality (B/C)</td><td colspan="2">B/C raised to a B</td></tr>
<tr><td>Fish</td><td>Floodplain dependent fish</td><td>Hydrology (C), geomorphology (C), water quality (B/C)</td><td colspan="2">C</td></tr>
<tr><td rowspan="2">Birds</td><td>White-faced duck</td><td>Hydrology (C), water quality (B/C), vegetation (C/D)</td><td>C</td><td rowspan="2">C raised to a B/C</td></tr>
<tr><td>White-breasted Cormorant</td><td>Vegetation (C/D), fish (C)</td><td>C</td></tr>
<tr><td>Mammals</td><td>Waterbuck</td><td>Hydrology (C), water quality (B/C), vegetation (C/D)</td><td colspan="2">C raised to a B/C</td></tr>
</table>

5.6 Description of scenarios

The first sets of data produced for the Nylsvley floodplain were the PES (2022) and Naturalised scenarios against which the DRIFT was calibrated:

- PES, which uses the climatic period of 1925-2021 with the water-resource developments, population, land use, etc. at 2022 levels.
- Naturalised, which uses the climatic period of 1925-2021 with the water-resource developments, population, land use, etc. at the estimated levels of around 1900.

Subsequently, a set of additional test or synthetic scenarios was created in order to test the model and the various hypotheses around required flooding regimes. The scenarios were:

- **Dry**: A set of 17 dry years from the modelled hydrology that was repeated to make up the 96-year record. This served as an absolute worst case, but also a test whether the biota responded appropriately.

- **6Dry1Wet (6d1w)**: An average wet year (1979) was placed within the Dry time-series every seventh year, meaning that there were six dry years followed by one wet, and so on. This served to test to what extent a very much reduced flood regime within dry years would allow any recovery of the biota.
- **4Dry1Wet1Dry1Wet (4d1w-1d1w)**: An average wet year (1979) was placed within the Dry time-series every fifth year and seventh year, meaning that there were four dry years followed by one wet, followed by a dry and a wet year, and so on. This served to test to what extent a less severely reduced flood regime between dry years would allow any recovery of the biota.
- **2Dry1Wet-20Wetter (2d1w-20W)**: An average wet year (1979) was placed within the Dry time-series every third year, with a wetter year (1995) replacing the wet year roughly every 20 years (to coincide with wetter periods or years within the flow record). This served to test whether the suggested flood regime, in particular for the middle range floods, would improve the condition of the biota relative to 6d1w and 4d1w1d1w.

To choose dry years, the daily regime was analysed in various ways:

- For each zone, the depth of the reach was calculated, and those years whose average, minimum and maximum were less than the 25th percentile were categorised as dry.
- For each zone, the floodplain area of the zone was calculated, and those years whose average, minimum and maximum were less than the 25th percentile were categorised as dry.
- Common years across zones and for depth and floodplain area noted, and this resulted in the final set of 17 years, and the choice of 1979 as an “average” wet year, and 1995 as a “wetter” year.

5.6.1 Ecologically relevant flow indicators

Median values for the ecologically relevant hydrological and hydraulic indicators are provided in **Table** 5.16. The flow regime of the Naturalised scenario is wetter than PES at all sites while other scenarios are drier than PES. The most prominent changes in the drier scenarios are late onset of the wet season, shorter wet season duration and a drastic reduction in inundation duration at preferred depth ranges.

Table 5.16: Summary statistics for ecologically-relevant flow indicators in DRIFT-Nylsvley (all medians apart from * = mean)

Scenario	PES	Naturalised	Dry	6d1w	4d1w-1d1w	2d1w-20W
15_Nylsvley1						
Mean annual Area	0.827	1.026	0.185	0.200	0.214	0.224
Dry onset	14.000	14.000	15.500	11.000	8.000	8.000
Dry duration	246.000	226.000	262.000	265.000	273.000	263.500
Dry min 5d Area	0.012	0.013	0.011	0.011	0.011	0.011
Wet onset	45.000	44.500	10.000	13.000	43.000	43.000
Wet duration	91.500	114.500	53.000	58.000	70.000	90.000
Wet max 5d Area	6.037	6.308	2.194	2.374	2.646	2.708
Wet max inst 5d Area	7.200	7.432	3.043	3.243	3.312	3.638
Zero days per year	15.500	11.386	26.648	22.626	17.538	18.512
D: area Emergent vegetation	0.002	0.004	0.001	0.001	0.001	0.001
D: area FP Grass (central)	0.103	0.162	0.041	0.050	0.073	0.075
D: area FP Grass (edge)	0.029	0.049	0.010	0.012	0.019	0.019
D: area Shrubs / trees	0.001	0.002	0.001	0.001	0.001	0.001
D: area Trees	0.022	0.028	0.014	0.015	0.018	0.018
W: area Emergent vegetation	0.023	0.028	0.002	0.002	0.003	0.003
W: area FPGrass (central)	0.720	0.894	0.088	0.097	0.104	0.114
W: area FP Grass (edge)	0.257	0.324	0.024	0.026	0.032	0.037

Scenario	PES	Naturalised	Dry	6d1w	4d1w-1d1w	2d1w-20W
W: area Shrubs / trees	0.026	0.031	0.001	0.001	0.002	0.002
W: area Trees	0.066	0.083	0.020	0.021	0.022	0.022
Dur Emergents	36.977	50.257	7.226	9.319	13.686	15.827
Dur FP Grass (central)	69.197	77.738	16.524	18.819	30.757	32.311
Dur FP Grass (edge)	36.881	44.737	7.118	8.964	13.225	15.397
Dur Shrubs / Trees	23.915	29.263	3.000	4.000	7.944	13.511
Dur Trees	192.741	249.040	96.638	107.058	145.695	143.957
D: avemax Depth Aquatic	0.413	0.539	0.261	0.277	0.349	0.345
D: avemax Depth FP grass (central)	0.854	1.020	0.633	0.670	0.769	0.754
D: avemax Depth FP grass edge)	0.588	0.761	0.365	0.403	0.498	0.487
D: maxmax Depth Aquatic	1.568	1.593	1.333	1.463	1.558	1.568
D: maxmax Depth FP grass (central)	2.454	2.484	2.119	2.299	2.439	2.454
D: maxmax Depth FP grass edge)	2.261	2.291	1.926	2.106	2.246	2.261
W: avemax Depth Aquatic	1.163	1.263	0.399	0.417	0.446	0.454
W: avemax Depth FP grass (central)	1.868	1.979	0.795	0.832	0.879	0.877
W: avemax Depth FP grass edge)	1.646	1.767	0.539	0.583	0.611	0.621
W: maxmax Depth Aquatic	2.008	2.033	1.263	1.443	1.508	1.538
W: maxmax Depth FP grass (central)	2.849	2.879	2.009	2.284	2.384	2.429
W: maxmax Depth FP grass edge)	2.656	2.686	1.816	2.091	2.191	2.236
Frequency Emergents *	0.354	0.406	0.000	0.000	0.146	0.052
Frequency FP grass (central) *	0.563	0.625	0.000	0.135	0.281	0.333
Frequency FP grass (edge) *	0.490	0.563	0.000	0.135	0.281	0.333
Frequency Shrubs / Trees *	0.417	0.500	0.000	0.135	0.281	0.333
Frequency Trees *	0.990	1.000	0.948	0.958	0.969	0.969
16_Nylsvley2						
Mean annual Area	1.792	2.083	1.111	1.163	1.206	1.210
Dry onset	20.000	20.500	18.000	19.000	19.000	19.000
Dry duration	199.500	184.500	230.000	229.000	215.000	217.000
Dry min 5d Area	0.384	0.833	0.375	0.352	0.363	0.333
Wet onset	45.000	46.000	13.000	24.500	43.000	46.000
Wet duration	132.500	161.500	39.000	43.000	57.000	61.000
Wet max 5d Area	5.263	5.446	2.351	2.470	2.486	2.661
Wet max inst 5d Area	5.576	5.830	2.403	2.509	2.599	2.763
Zero days per year	9.030	0.000	14.285	11.495	10.150	11.368
D: area Emergent vegetation	0.002	0.003	0.002	0.002	0.002	0.002
D: area FP Grass (central)	0.257	0.310	0.228	0.234	0.246	0.240
D: area FP Grass (edge)	0.307	0.416	0.235	0.245	0.267	0.255
D: area Shrubs / trees	0.072	0.100	0.053	0.054	0.060	0.060
D: area Trees	0.051	0.076	0.037	0.038	0.042	0.042
W: area Emergent vegetation	0.013	0.014	0.003	0.003	0.003	0.004
W: area FPGrass (central)	0.440	0.457	0.286	0.294	0.305	0.307
W: area FP Grass (edge)	0.660	0.689	0.347	0.370	0.390	0.397
W: area Shrubs / trees	0.257	0.278	0.082	0.091	0.097	0.100
W: area Trees	0.226	0.246	0.060	0.068	0.073	0.076
Dur Emergents	38.102	43.380	3.998	5.962	19.147	25.942
Dur FP Grass (central)	84.6337	101.4420	19.254	20.7	42.9	49.8
Dur FP Grass (edge)	16.948	19.510	0.000	0.266	7.402	13.814
Dur Shrubs / Trees	8.297	9.798	0.000	0.000	2.929	5.777
Dur Trees	12.675	14.290	0.000	0.000	4.606	7.554
D: avemax Depth Aquatic	0.811	0.938	0.743	0.752	0.777	0.767
D: avemax Depth FP grass (central)	1.505	1.614	1.449	1.456	1.478	1.464
D: avemax Depth FP grass edge)	1.123	1.215	1.067	1.072	1.095	1.083
D: maxmax Depth Aquatic	1.203	1.310	1.186	1.205	1.228	1.215
D: maxmax Depth FP grass (central)	1.675	1.750	1.675	1.695	1.725	1.705
D: maxmax Depth FP grass edge)	1.395	1.495	1.375	1.395	1.395	1.395
W: avemax Depth Aquatic	1.184	1.209	0.861	0.893	0.909	0.925
W: avemax Depth FP grass (central)	1.767	1.783	1.568	1.585	1.601	1.606
W: avemax Depth FP grass edge)	1.385	1.404	1.159	1.179	1.188	1.207
W: maxmax Depth Aquatic	1.586	1.617	1.270	1.300	1.308	1.310
W: maxmax Depth FP grass (central)	2.269	2.289	1.715	1.725	1.754	1.764
W: maxmax Depth FP grass edge)	1.845	1.880	1.445	1.485	1.485	1.490

Scenario	PES	Naturalised	Dry	6d1w	4d1w-1d1w	2d1w-20W
Frequency Emergents *	0.354	0.427	0.000	0.135	0.281	0.333
Frequency FP grass (central) *	0.677	0.771	0.000	0.135	0.281	0.333
Frequency FP grass (edge) *	0.208	0.240	0.000	0.135	0.281	0.333
Frequency Shrubs / Trees *	0.156	0.167	0.000	0.000	0.000	0.052
Frequency Trees *	0.250	0.271	0.000	0.135	0.281	0.333
17_Nylsvley3						
Mean annual Area	2.951	3.461	1.472	1.603	1.657	1.671
Dry onset	19.500	20.500	14.000	15.000	19.000	19.000
Dry duration	222.000	188.500	280.000	267.000	254.000	241.500
Dry min 5d Area	0.588	1.218	0.552	0.561	0.568	0.569
Wet onset	41.500	46.000	13.000	13.000	17.000	15.500
Wet duration	133.000	155.500	13.000	31.000	33.000	39.000
Wet max 5d Area	9.277	9.575	3.353	3.521	3.729	3.866
Wet max inst 5d Area	9.647	10.087	3.505	3.583	3.825	4.011
Zero days per year	11.337	0.000	29.772	23.793	15.927	15.339
D: area Emergent vegetation	0.004	0.007	0.002	0.002	0.003	0.003
D: area FP Grass (central)	0.370	0.523	0.264	0.306	0.337	0.341
D: area FP Grass (edge)	0.296	0.401	0.227	0.254	0.276	0.277
D: area Shrubs / trees	0.086	0.104	0.074	0.078	0.083	0.085
D: area Trees	0.128	0.155	0.107	0.116	0.124	0.126
W: area Emergent vegetation	0.031	0.035	0.005	0.005	0.006	0.006
W: area FPGrass (central)	1.510	1.617	0.425	0.467	0.489	0.525
W: area FP Grass (edge)	0.975	1.046	0.337	0.353	0.377	0.391
W: area Shrubs / trees	0.286	0.318	0.092	0.096	0.099	0.104
W: area Trees	0.469	0.521	0.140	0.144	0.152	0.158
Dur Emergents	66.358	78.872	6.627	14.417	34.848	41.537
Dur FP Grass (central)	113.072	139.606	20.468	32.040	67.959	76.478
Dur FP Grass (edge)	97.052	119.118	12.111	20.936	52.737	60.544
Dur Shrubs / Trees	40.977	48.502	0.000	0.000	22.916	32.668
Dur Trees	74.758	86.096	2.149	5.929	38.034	48.579
D: avemax Depth Aquatic	0.612	0.646	0.580	0.593	0.612	0.610
D: avemax Depth FP grass (central)	1.855	1.871	1.842	1.848	1.852	1.853
D: avemax Depth FP grass edge)	1.768	1.782	1.758	1.761	1.765	1.765
D: maxmax Depth Aquatic	0.719	0.788	0.674	0.709	0.729	0.729
D: maxmax Depth FP grass (central)	1.895	1.925	1.885	1.895	1.905	1.905
D: maxmax Depth FP grass edge)	1.809	1.819	1.789	1.799	1.809	1.809
W: avemax Depth Aquatic	0.842	0.861	0.632	0.638	0.644	0.648
W: avemax Depth FP grass (central)	1.969	1.982	1.860	1.865	1.868	1.871
W: avemax Depth FP grass edge)	1.852	1.860	1.772	1.775	1.778	1.782
W: maxmax Depth Aquatic	1.159	1.164	0.734	0.749	0.749	0.749
W: maxmax Depth FP grass (central)	2.155	2.165	1.905	1.905	1.915	1.915
W: maxmax Depth FP grass edge)	1.989	1.989	1.809	1.809	1.819	1.819
Frequency Emergents *	0.573	0.667	0.000	0.135	0.281	0.333
Frequency FP grass (central) *	0.760	0.906	0.063	0.198	0.333	0.375
Frequency FP grass (edge) *	0.792	0.885	0.063	0.198	0.333	0.375
Frequency Shrubs / Trees *	0.573	0.615	0.000	0.135	0.281	0.333
Frequency Trees *	0.740	0.833	0.000	0.135	0.281	0.333

5.7 Outcomes of the scenario analyses

The outcomes of the flow scenarios are summarised as daily time-series for the riverine biota (**Section 5.7.1**), percentage changes in median abundance of riverine biota relative to PES (**Section 5.7.2**) and on the overall ecological integrity (**Section 5.7.3**).

In the calculation of integrity for each EWR zone all disciplines and indicators were given equal weights. The overall integrity of the floodplain was calculated by combining the outcomes for the three EWR zones. The zones were given equal weights.

5.7.1 Time series of responses of riverine biota

The abundance of all the floodplain vegetation (aquatic vegetation, reeds and central and edge floodplain grasses) was higher under the Naturalised flow scenario when compared to PES and lower in the other drier flow scenarios (**Figure** 5-18).

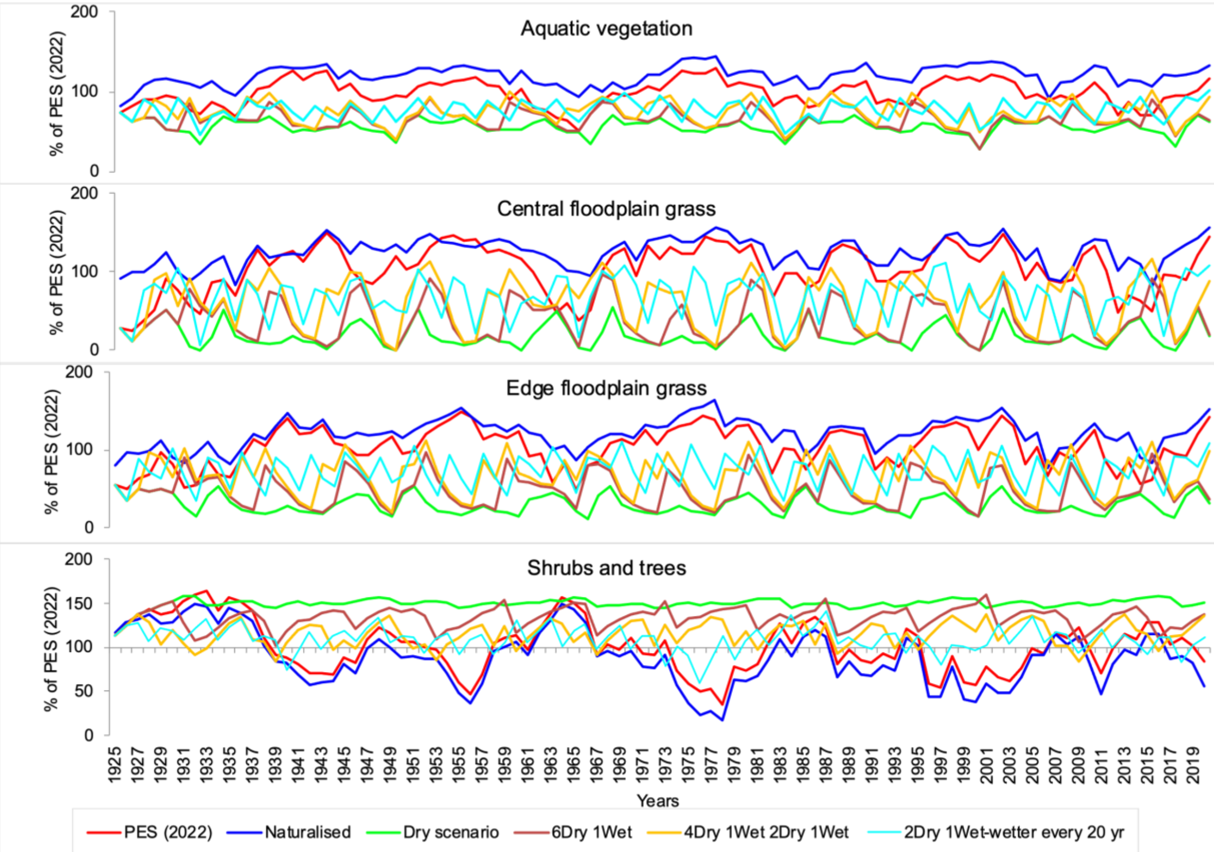

Figure 5-18: Time-series of abundance of vegetation relative to PES

The terrestrial trees and shrubs were more abundant under the Dry scenario, otherwise were less abundant than the vegetation on the floodplain in all the other scenarios because they get drowned out. The abundance of central and edge floodplain grasses was lower than aquatic vegetation and reeds in the Dry scenario because of a negative feedback link to the abundance of trees and shrubs that shade them out as the terrestrial plants move onto the floodplain. All the floodplain vegetation (aquatic vegetation, reeds and central and edge floodplain grasses) show a severely negative response to the Dry scenario and unlike the other scenarios do not recover because there are no wet years. The time frame for recovery is quicker as the scenarios become progressively wetter.

The abundance of all the biota was higher under the Naturalised flow scenario when compared to PES, and lowest in the Dry scenario (**Figure** 5-19).

Figure 5-19: Time-series of abundance of biota relative to PES

The abundance of Coenagrionids follows the responses predicted for aquatic vegetation (**Figure** 5-18) because they inhabit the slow-flowing and vegetated aquatic habitats at the edges of the channel and in the backwaters. The abundances of floodplain dependent fish and waterbirds are more responsive to changes in the Dry and drier flow scenarios with progressively wetter conditions because they are linked to changes in the floodplain vegetation, which show a more varied response. The waterbuck are expected to have a more muted response to the drier flow scenarios because they are less dependent on changes in the floodplain vegetation being able to switch from grazing grasses to browsing leaves and twigs on the terrestrial shrubs and trees when needed.

5.7.2 Mean percentage changes in abundance of riverine biota

The outcomes of the flow scenarios on the overall abundance in the indicators are shown in **Table** 5.17. Warm colours indicate reductions in abundance relative to PES and cool colours increases. The main responses predicted were for:

- Severe reductions in the abundance of reeds and of central and edge floodplain grasses in all the zones and the most severe reductions at 16_Nylsvley2 and 17_Nylsvley3.

- Large reductions in fish and water birds driven by the severe reductions in floodplain vegetation on the floodplain.
- Less severe reductions in the abundance of aquatic vegetation and therefore in Coenagrionids.
- Moderate reductions in water buck outside of the Nylsvley Nature Reserve, in zones 15_Nylsvley1 and 17_Nylsvley3 that are supported by the increase in trees and shrubs that provide nourishment when the floodplain vegetation suffers under the dry scenarios.

Table 5.17: Mean percentage changes in riverine biota relative to PES

Riverine biota	PES	Nat	Dry	6d1w	4d1w-1d1w	2d1w-20W
15_Nylsvley1						
Vegetation						
Aquatic vegetation	1.68	13.86	-26.71	-20.60	-15.83	-14.10
Reeds	0.83	10.27	-39.46	-30.71	-22.01	-19.21
Central floodplain grass	1.81	13.99	-60.58	-48.21	-33.32	-30.73
Edge floodplain grass	2.56	10.09	-46.87	-35.56	-24.67	-19.79
Shrubs and trees	1.73	-9.13	28.79	19.20	8.38	0.38
Macroinvertebrates						
Coenagrionidae	0.26	6.68	-14.18	-10.76	-8.11	-7.20
Fish						
Floodplain dependent fish	0.94	9.97	-33.99	-26.53	-18.59	-18.06
Birds						
Cormorant	1.94	13.73	-44.22	-34.78	-27.12	-26.66
White-faced duck	-0.10	11.26	-29.14	-22.05	-16.29	-14.38
Mammals						
Water buck	3.45	4.79	-21.19	-13.73	-8.18	-7.19
16_Nylsvley2						
Vegetation						
Aquatic vegetation	-1.90	25.84	-32.66	-26.11	-18.01	-18.02
Reeds	0.58	12.89	-55.66	-39.43	-23.83	-18.38
Central floodplain grass	2.17	16.46	-72.77	-53.81	-32.44	-24.80
Edge floodplain grass	1.09	10.98	-42.77	-27.94	-15.59	-7.04
Shrubs and trees	-0.85	-7.86	48.58	31.79	18.58	0.61
Macroinvertebrates						
Coenagrionidae	-1.55	12.50	-17.17	-13.64	-9.25	-9.32
Fish						
Floodplain dependent fish	-1.35	18.53	-31.25	-24.35	-15.58	-16.03
Birds						
Cormorant	-1.14	19.64	-37.92	-29.14	-19.09	-22.65
White-faced duck	-1.27	22.25	-42.78	-32.06	-20.68	-19.37
Mammals						
Water buck	1.22	10.85	-17.25	-12.82	-7.98	-8.13
17_Nylsvley3						
Vegetation						
Aquatic vegetation	-1.63	21.22	-38.70	-29.69	-20.93	-17.97
Reeds	2.61	12.66	-50.58	-38.55	-22.89	-22.38
Central floodplain grass	2.00	16.71	-76.74	-59.05	-38.03	-33.71
Edge floodplain grass	1.89	15.55	-68.40	-51.93	-34.58	-31.02
Shrubs and trees	-1.74	-13.37	52.23	35.58	14.83	9.23
Macroinvertebrates						
Coenagrionidae	-1.47	10.36	-20.38	-15.50	-10.79	-9.20
Fish						
Floodplain dependent fish	0.33	16.78	-39.83	-29.89	-20.82	-17.61

Riverine biota	PES	Nat	Dry	6d1w	4d1w-1d1w	2d1w-20W
Birds						
Cormorant	0.49	19.09	-39.41	-31.03	-25.23	-23.61
White-faced duck	-1.25	18.39	-42.12	-31.38	-21.20	-18.69
Mammals						
Water buck	2.45	12.29	-25.53	-17.08	-11.20	-9.49

5.7.3 Overall ecosystem integrity

The overall integrity of the Nyl River floodplain is expected to drop from a C category under the PES scenario, to a D/E under the Dry scenario, a D under the 6d1w, a high D under the 4d1w-1d1w and a C/D under the 2d1w-20W scenario (**Figure** 5-20). The increase in integrity from 6d1w to 4d1w-1d1w shows the benefit of more regular floods, although they are not at the recommended frequency. The additional increase in integrity under 2d1w-20W shows the additional benefit of floods every three years, plus a slight benefit from the occasional higher level wet year.

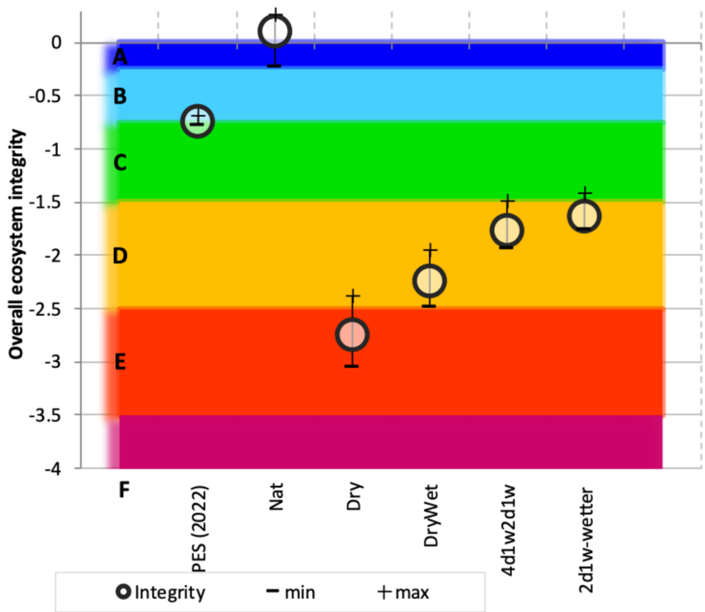

Figure 5-20: Overall ecosystem integrity of the Nyl River floodplain per scenario

The changes in each discipline are shown in **Table** 5.18 and show that under the least dry synthetic scenario (2d1w-20W) vegetation, invertebrates and fish drop by one category, birds by one and a half categories and mammals by half a category.

Table 5.18: Ecological categories predicted under the scenarios per discipline

	PES (2022)	Nat	Dry	6d1w	4d1w-1d1w	2d1w-20W
Vegetation	C/D	B	F	E/F	D/E	D/E
Inverts	B	A	C/D	C	C	C
Fish	C	A	E	D/E	D	D
Birds	B/C	A	E	D/E	D	D
Mammals	B/C	A	D	C/D	C	C
Overall	**C**	**A**	**D/E**	**D**	**D**	**C/D**

5.8 Floods and EWRs

The Nyl River floodplain is an extensive floodplain wetland along a ~75-km length of the Nyl River, which has a shallow and meandering channel. It is the only wetland in South Africa that supports a population of Wild Rice (*Oryza longistaminata;* Gibbs Russell *et al*. 1991). The key driver for biological processes and subsequent high biodiversity on the floodplain is lateral connectivity between the river and the floodplain (Kingford 2000) driven by the extent to which floods inundate the floodplain.

5.8.1 Inundation of the floodplain under PES conditions

Rejuvenation and growth of the floodplain grasses supports the entire floodplain ecosystem so the central and edge floodplain grasses are the most important ecological attribute of the Nyl River floodplain. The central floodplain grasses are inundated more regularly and for longer than grasses around the edge. The extent to which higher or lower discharge inundates more or less of the floodplain grasses is shown in **Table** 5.19.

For example, a discharge of 20m^3/s inundates approximately:

- 70-79% of central and 50-59% of edge floodplain grasses at 15_Nyl1
- 80-89% of central and 80-89% of edge floodplain grasses at 16_Nyl2
- 90-99% of central and 80-89% of edge floodplain grasses at 17_Nyl3.

Table 5.19: Area of central and edge floodplain grasses flooded at different discharges in the Nyl River

Area floodplain grasses inundated (%)	15_Nylsvley1		16_Nylsvley2		17_Nylsvley3	
	Central	Edge	Central	Edge	Central	Edge
	Discharge (m^3/s)					
40 – 49	5.9	14.8	2.5	4.2	5.5	5.9
50 - 59	9.6	19.9	3.8	5.9	6.1	8.3
60 - 69	14.1	28.0	5.4	10.5	8.7	12.8
70 - 79	20.6	38.5	10.2	15.5	13.2	15.8
80 - 89	33.3	64.0	15.9	21.1	16.9	20.8
90 - 99	65.7	71.8	30.6	50.1	18.8	31.0
100	104.8	104.8	108.7	108.7	40.12	40.1

Since there are no water-resource developments planned that are expected to affect water supply to the Nyl River floodplain, the objective of the EWR is to maintain the PES (2022) conditions. The EWRs provided are flood requirements to inundate the floodplains grassland, and inflows from two of its main tributaries, the Groot Nyl and Olifantspruit Rivers. EWRs were determined for the Olifantspruit River at 3_Olifantspruit that are provided in the River Assessment (Volume3): Ecological Water Requirements Report.

5.8.2 Ecological Water Requirements

5.8.2.1 Flood requirements for the floodplain

The objective of the flood requirements is to inundate 60-80% of central floodplain grasses with small floods, 70 – 90% with a medium flood and 80 - 100% with a large flood, and that the return period of these floods would roughly match that described by Higgins *et al*. (1996): channel flows in 7 of 10 years (small floods), floodplain inundation in 4 of 10 years (medium floods) and large floods in 2 of 10 years.

The flood requirements and the extent to which they inundate the floodplain grasses are outlined in **Table** 5.20.

Table 5.20: Magnitude, return period and extent to which the floods inundate the floodplain to maintain PES conditions at the Nyl River floodplain

Return period / flood frequency	Flood magnitude (m3/s)	15_Nyl 1		16_Nyl 2		17_Nyl 3	
		Central	Edge	Central	Edge	Central	Edge
		% area of floodplain grasses inundated					
1:1	3 - 5	30-39	10-19	50-59	40-49	30-39	30-39
1:2	16 - 20	60-69	50-59	80-89	70-79	90-99	70-79
1:3	28 - 30	70-79	60-69	80-89	80-89	90-99	80-89
1:5	45 -50	80-89	70-79	90-99	80-89	100	100

The flood requirements are:

- a 3 - 5 m^3/s annual flood
- a 16 - 20 m^3/s flood every two years for a duration of 3 to 4 months
- a 28 - 30 m^3/s flood every three years for 50[70] to 90 days
- a 45 - 50 m^3/s flood every five years for 90 to -150[71] days.

The duration of the flood events does not refer to the duration of peak inflows, of which there could be several that contribute to a single flood event. It described retention of flood waters on the floodplain during flood recession behind levees and in depressions on the floodplain.

[70] 50 days is the minimum duration for successful bird breeding

[71] 150 days being optimum for *Oryza longistaminata* to effectively complete its life cycle (Marneweck pers. comm. 2023)

5.8.2.2 Lowflows and floods in the tributaries

There are seven main tributaries of the Nyl River that flow into the floodplain:

- the Groot Nyl, Klein Nyl, Olifantspruit and Middlefontein rivers that flow into 15_Nylsvley1
- the de Wetspruit and Blindefontein that flow into 16_Nylsvley2
- and Badseloop that flows into 17_Nylsvley3.

The lowflow and flood requirements are provided from the Olifantspruit (corresponding with the river EWR site 3_Olifantspruit, and the Nyl River downstream of the confluence of the Klein Nyl and Groot Nyl rivers, i.e. the inflows at the upstream end of the Nyl River floodplain.

The EWRs are:

- Inflows from the Nyl River at the N1 to maintain the PES (2022) of a C for the Nyl River floodplain (**Table** 5.21).
- Inflows from the Olifantspruit to maintain the PES (2022) of a C at the river EWR site 3_Olifantspruit and the PES (2022) of a C for the Nyl River floodplain (**Table** 5.22).

Table 5.21: EWRs of the Nyl River at the N1 to maintain a C for the Nyl River floodplain

nMAR	61.871	MCM			
S.Dev.	2.659				
CV	0.043				
Q75	0.080				
Ecological Category	C				
	MCM	% nMAR	Excludes floods with return period ≥1:2 years.		
Total EWR	43.963	71.055			
Maint. Lowflows	24.145	39.024			
Drought Lowflows	12.016	19.420			
Maint. Highflows	19.818	32.031			
Monthly Distributions (MCM)					
	Natural	Modified Flows (EWR)			
		Lowflows		Highflows	Total EWR
Month	Mean	Maint.	Drought	Maint.	Maint.
Oct	1.622	0.552	0.526	0.202	0.754
Nov	4.513	1.462	0.865	2.116	2.876
Dec	7.585	2.163	1.163	4.314	5.113
Jan	9.294	2.544	1.272	5.631	6.380
Feb	11.553	3.513	1.541	7.202	7.449
Mar	9.212	3.330	1.418	5.202	6.884
Apr	5.944	2.817	1.178	2.621	5.319
May	3.845	2.369	1.030	0.990	3.299
Jun	2.734	1.948	0.901	0.303	2.251
Jul	2.243	1.601	0.817	0.096	1.698
Aug	1.836	1.108	0.712	0.053	1.161
Sep	1.491	0.739	0.593	0.040	0.778
Total	61.87	24.14	12.02	28.77	43.96

Floods. Flood can occur in the month before or after the month indicated								
	Within year floods <1:2 years				Inter annual floods >=1:2 years			
Flood Class	Class1	Class2	Class3	Class4	1:2	1:5	1:10	1:20
Ave peak discharge (m^3/s)	1.40	2.90	5.60	10.90	22	40	53	106
Ave duration (days)	8	8	10	10	10	18	8	15
Number	6	5	3	2				
Oct								
Nov								
Dec	1							
Jan	1	2						
Feb	1	1	1	1	1	1	1	1
Mar	1	1	1	1				
Apr	1	1	1					
May	1							
Jun								
Jul								
Aug								
Sep								
Vol ($10^6 m^3$)	2.73	3.64	4.99	5.69	6.01	10.87	9.42	22.93
% PES (2022) MAR	5.16	6.87	9.43	10.75	11.35	20.55	17.80	43.33

Table 5.22: EWRs to maintain a C category at the Olifantspruit to maintain a Nyl River floodplain in a C

REC:	Base		
nMAR	7.815	MCM	
S.Dev.	0.784		
CV	0.100		
Q75	0.0111		
Ecological Category	C		
	MCM	% MAR	
Total IFR	6.002	76.792	
Maint. Lowflow	3.385	43.318	Excludes floods with return period ≥1:2 years.
Drought Lowflow	1.513	19.354	
Maint. Highflow	2.616	33.474	

Monthly Distributions (MCM)					
	Natural	Modified Flows (IFR)			
		Low flows		High Flows	Total Flows
Month	Mean	Maint.	Drought	Maint.	Maint.
Oct	0.147	0.089	0.059	0.012	0.101
Nov	0.605	0.259	0.130	0.303	0.475
Dec	1.171	0.399	0.194	0.716	0.884
Jan	1.407	0.494	0.222	0.853	1.064
Feb	1.641	0.578	0.235	1.003	1.166
Mar	1.355	0.549	0.219	0.751	1.024
Apr	0.686	0.392	0.158	0.261	0.629
May	0.297	0.229	0.096	0.041	0.261
Jun	0.154	0.132	0.058	0.001	0.133
Jul	0.125	0.103	0.049	0.001	0.103
Aug	0.116	0.087	0.046	0.000	0.087
Sep	0.111	0.075	0.048	0.000	0.075
Total	7.82	3.39	1.51	3.94	6.00

Floods. Flood can occur in the month before or after the month indicated								
	Within year floods <1:2 years				Inter annual floods >=1:2 years			
Class	Class1	Class2	Class3	Class4	1:2	1:5	1:10	1:20
Ave peak discharge (m^3/s)	0.60	0.90	1.70	3.40	6	11	14	24
Ave duration (days)	3	4	7	8	10	8	11	13
Number	2	2	1	1	As per return period			
Oct								
Nov	1							
Dec		1						
Jan			1					
Feb				1	1	1	1	1
Mar		1						
Apr	1							
May								
Jun								
Jul								
Aug								
Sep								
Vol (10^6m^3)	0.142	0.339	0.485	0.916	1.74	2.15	3.39	5.05
% Base nMAR	1.943	4.629	6.616	12.501	23.78	29.31	46.29	68.89

6 LUVUVHU RIVER FLOODPLAIN EWR

6.1 Introduction

The 7 756-ha Makuleke wetland is situated along the Limpopo and Luvuvhu Rivers and is known for its diverse and rich wildlife (Ramsar Information Sheet 2007 and 2017). It was registered as a Ramsar site in 2007 and comprises riverine forests, riparian floodplain forests, floodplain grasslands, river channels, perennial and seasonal pans that create habitat for a multitude of water birds, and water-dependent reptiles and mammals. The Luvuvhu River flows into the Limpopo River and the interactions between the two rivers are hydraulically complex at their confluence and important for the ecological functioning of the Luvuvhu River floodplain, which makes up a large portion of the Makuleke wetland complex. Riverine forest is mostly confined to the banks of the Limpopo and Luvuvhu rivers, and consists of large, broad canopied trees >20-m tall. Floodplain vegetation comprises either floodplain forests, with notable Fever tree forests, floodplain shrubs or floodplain grasslands (Venter 1990) with 31 pans scattered on the floodplain (**Figure** 6-1; Ramsar Information Sheet, 2007 and 2017). Pans are either aligned with floodplain features along the Limpopo River, or with one of two paleochannels on the Luvuvhu floodplain, one to the north of the Luvuvhu River and one to the south, known as the Hapi River. These paleochannels are vital in this ecosystem as they hold water throughout the dry season. The floodplains are also important for groundwater recharge that maintains riparian and floodplain vegetation. The depth to groundwater is shallow (2.4 – 6.8 m; Ramsar Information Sheet 2007) and phreatophytic woody trees access this water to persist through the dry season.

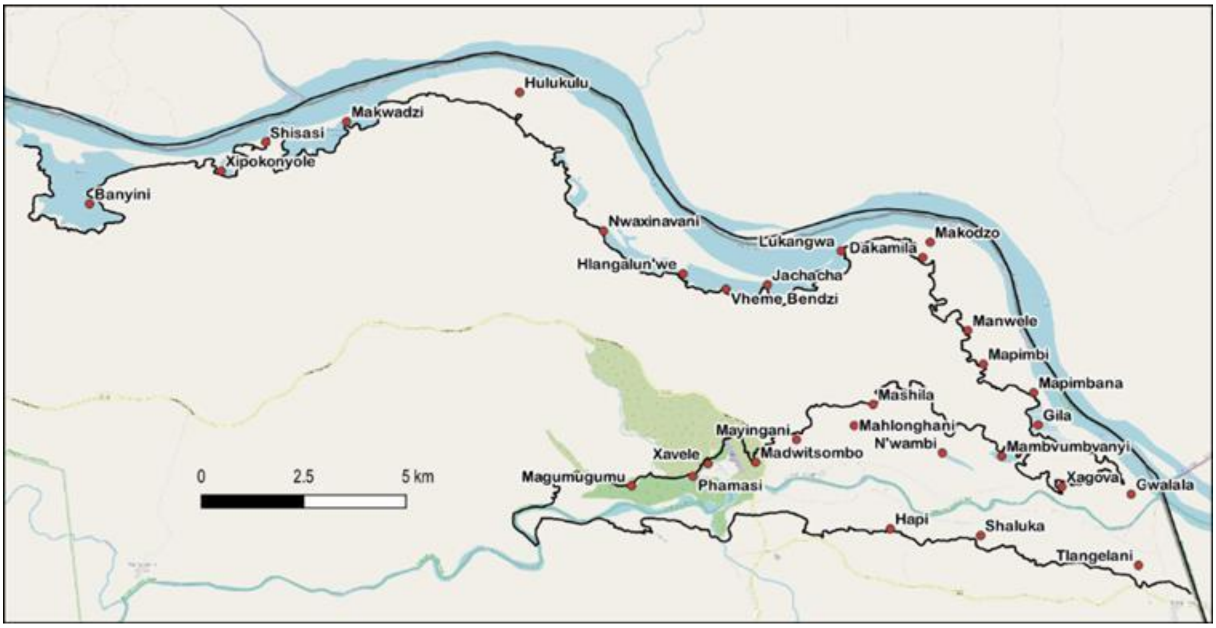

Figure 6-1: Map showing the Limpopo and Luvuvhu floodplains and the pans that comprise the Makuleke wetland complex

Four hundred and fifty bird species are listed for the Luvuvhu floodplain (Sinclair and Whyte 1992) and is home to large populations of the rare Pel's fishing owl (*Scotopelia peli*) and the rare pygmy goose (*Nettapus auritus*) in Africa. The waterbird communities of the Makuleke wetland complex are an integral part of the ecosystem, and the pans provide habitat during both summer and winter months and serve as a stopover for many migratory waterbirds (Ramsar Information Sheet, 2007 and 2017).

Twenty-seven mammals are listed as using the pans (Antrobus 2014). These include the samango monkey, bushpig, hippopotamus, nyala, waterbuck, warthog, vervet monkeys (Smithers 1986) and there are two herds of buffalo and elephants resident on the floodplain (Ramsar Information Sheet, 2007 and 2017 update by A.R. Deacon).

The hippopotamus is Vulnerable on the IUCN Red List (Lewison and Pluháček 2017) and occurs in the deep pools of the Luvuvhu River and the Nwambi, Hapi and Tlangelani pans (Ramsar Information Sheet 2007 and 2017). The numbers of hippopotami dropped to 10 animals after the drought in 1992/93 (Viljoen 1995). Aside from poachers, the biggest threat to the hippopotami is an altered flow regime that will reduce the frequency of floods that breach the floodplain levees to inundate the floodplain that initiate growth of floodplain grasses and fill the pans, and the perenniality of the Luvuvhu River that controls the depth of pools in the river.

The flooding regimes of the Luvuvhu and Limpopo rivers drive the complexity and composition of the Makuleke wetland complex and are vital for its ecological integrity. The Luvuvhu River floodplain floods in three ways: the Luvuvhu River breaching its banks, which occurs roughly every 8 to 10 years (Bruwer 1987); back flooding in an upstream direction when the Limpopo River floods and pushes up the Luvuvhu River, which occurs every ~2 to 3 years, and direct input from rainfall and smaller catchment and tributary flows during rain events. Added to this complexity, flooding characteristics are influenced by the complex interaction between the Luvuvhu and Limpopo rivers with a combination of flooding possibilities. This complexity has been incorporated into the hydraulic modelling for the floodplain.

6.2 EWR sites

There are six EWR sites on the Luvuvhu River floodplain (**Figure** 6-2**)**:

- 18_Luvuvhu2 - is an important breach point where the Luvuvhu River overtops its banks and floods the floodplain.
- 19_Nwambi Pan - is a perennial, or near-perennial pan on the northern Luvuvhu floodplain that supports tall floodplain trees, crocodiles and a large pod of hippos and is flooded by both the Luvuvhu and Limpopo Rivers.
- 20_Mambvumbvanyi Pan - is a seasonal pan on the northern Luvuvhu floodplain that supports Fever tree forests, seasonal emergent floodplain vegetation and is flooded by both the Luvuvhu and Limpopo rivers.
- 21_Hapi Pan - is a perennial, or near-perennial pan on the southern Luvuvhu floodplain that supports crocodiles and hippos and is filled by flooding from the Luvuvhu River and lateral inputs from ephemeral drainage channels.
- 22_Tlangelani Pan - is a seasonal pan on the southern Luvuvhu floodplain that supports floodplain grasslands and is flooded by both the Luvuvhu and Limpopo rivers.
- 23_Luvuvhu3 - is a river site on the Luvuvhu River at the confluence with the Limpopo River that is important because deep pools support hippos and crocodiles in the dry season and droughts.

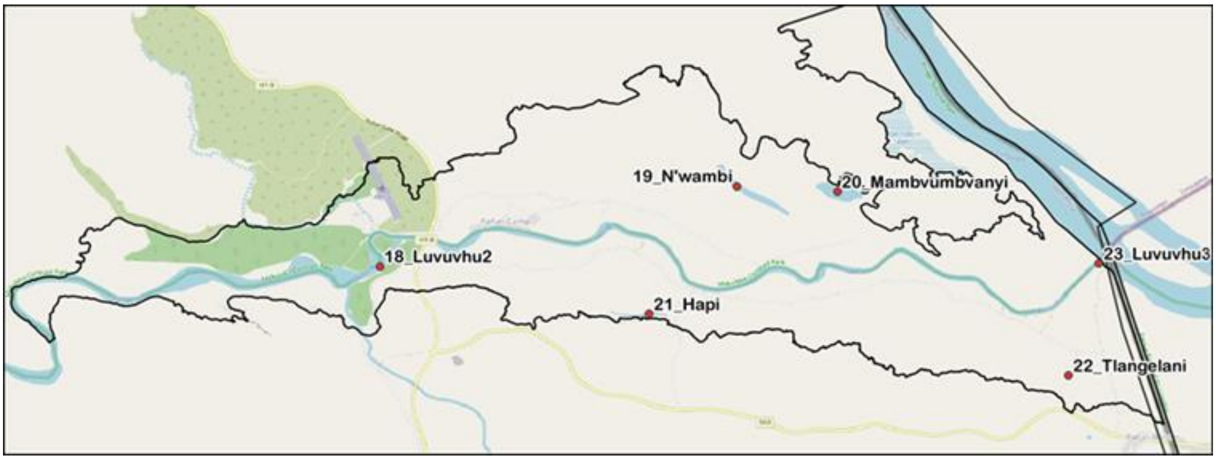

Figure 6-2: The 6 EWR sites on the Luvuvhu floodplain

6.2.1 18_Luvuvhu2

18_Luvuvhu2 is a wide channel, confined by distinct banks and dominated by alluvial features (**Figure** 6-3). Banks have well-defined riparian vegetation dominated by trees and shrubs, many of which are tall with wide canopies. The site is placed at the point where the Luvuvhu River breaches its banks during high, infrequent floods and occurs upstream of the bridge near the old Bobomene research station and campsite (**Figure** 6-3**)**. Flood breaches at this point occur at ~ 1 000 m^3/s every 8 years or so and are important for all the floodplain features along the Hapi drainage channel, but are impeded by the road through the floodplain, even though several culverts have been installed.

Figure 6-3: One of the breach points on the Luvuvhu River, looking upstream in October 2022, inset is looking downstream (left); satellite image (Bing, November 2018) showing surveyed and sampled waypoints (red, right)

6.2.2 19_Nwambi pan

19_Nwambi pan is on the northern side of the Luvuvhu floodplain (**Figure** 6-4). The pan is near perennial, inhabited by hippopotami and crocodiles and dries out in drought years. Nwambi pan is important to the ecological integrity of the Luvuvhu floodplain because of its large size (~1.3-km long and 90-m wide), depth (≤2.9 m) and near perenniality. The vegetation surrounding Nwambi comprises tall floodplain trees that grow in close proximity to the pan, but towards the south-east side of the pan there are extensive Fever tree forests that extend toward Mambvumbvanyi pan and the Luvuvhu River.

Figure 6-4: Nwambi Pan in October 2022 with radio-controlled boat in the foreground measuring water depth, and slightly visible large pod of hippos in the background (left); satellite image (Bing, November 2018) showing surveyed and sampled waypoints (red, right)

6.2.3 20_Mambvumbvanyi pan

20_Mambvumbvanyi pan is on the northern side of the Luvuvhu floodplain (**Figure** 6-5). The pan is seasonal but supports extensive emergent wetland non-woody vegetation when it holds water. Mambvumbvanyi is oval shaped (570 x 230 m), with maximum depth of ~2.0 m when the pan overflows. The vegetation surrounding Mambvumbvanyi comprises tall Fever tree forests that extend toward Nwambi pan and the Luvuvhu River all the way to the confluence with the Limpopo River.

Figure 6-5: Mambvumbvanyi Pan and extensive Fever tree forests surrounding the pan in October 2022 (inset shows last standing water with trapped catfish, left); satellite image (Bing, November 2018) showing surveyed and sampled waypoints (red, right)

6.2.4 21_Hapi pan

21_Hapi pan is on the southern edge of the Luvuvhu floodplain (**Figure** 6-6). The pan is near perennial, although has dried out in drought years. It is inhabited by hippopotami and crocodiles. Hapi pan is important to the ecological integrity of the Luvuvhu floodplain because of its size (900 x 50 m), maximum depth of ~3.3 m before it overflows and near perenniality, which is aided by runoff into the pan during rainfall events from the southern side. The vegetation surrounding Hapi is mixed, with some tall floodplain trees that are confined to the edges of the pan, but mostly comprises sparse and opens areas with floodplain grasses and shrubs. Hapi pan is along the Hapi drainage channel which runs from the

Luvuvhu River at the Bobomene breach point (at 18_Luvuvhu2) through Tlangelani pan and into Mozambique before it joins the Limpopo River.

Figure 6-6: Hapi Pan in October 2022 (left); satellite image (Bing, November 2018) showing surveyed and sampled waypoints, inset is the pan dry (red, right)

6.2.5 22_Tlangelani pan

22_Tlangelani pan is on the southern side of the Luvuvhu floodplain along the Hapi River drainage channel (**Figure** 6-7). The pan is near perennial, inhabited by hippopotami and crocodiles and has dried out in drought years. Tlangelani Pan is important to the ecological integrity of the Luvuvhu floodplain due to its size (~1,120 x 70 m), depth (~ 2.1 m when it overflows) and near perenniality. The vegetation surrounding Tlangelani is mostly shrubs and grasses with scattered and isolated tall trees, notably Leadwoods (*Combretum imberbe*) and Lala Palms (*Hyphaene coriacea*).

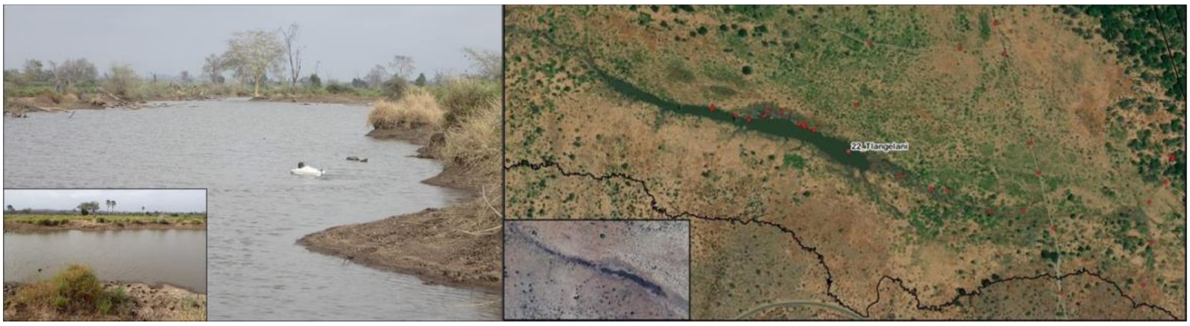

Figure 6-7: Tlangelani Pan in October 2022, inset shows mostly shrub and grass vegetation with scattered and isolated tall trees (left); satellite image (Bing, November 2018) showing surveyed and sampled waypoints, inset is the pan dry (red, right)

6.2.6 23_Luvuvhu3

23_Luvuvhu3 is on the Luvuvhu River at its confluence with the Limpopo River (**Figure** 6-8**)**. The channel is sandy and the banks have well-defined riparian vegetation dominated by trees and shrubs. The site was chosen because it is the largest pool during the dry season and is an important refuge for crocodiles and hippopotami.

Figure 6-8: The Luvuvhu River in October 2022 upstream of the confluence with the Limpopo (left); satellite image (Bing, November 2018) showing surveyed and sampled waypoints, inset is the pan dry (red, right)

6.3 Hydrological and hydraulic indicators

DRIFT-Luvuvhu used modelled hydrology for the river sites and depths for the pan sites as the main (driving) input data.

All the time-series use the same period: 1955-2011. Once imported into DRIFT-Luvuvhu, the time-series were summarized into ecologically relevant 'driver' indicators, reported as annual values or as values for one or more of four hydrobiological flow seasons (**Section 2.2.3**):

- Dry Season (Dry).
- Transition Season 1 (T1)
- Flood/Wet Season (Flood)
- Transition Season 2 (T2).

The indicators created using these time-series' and the seasons for which they were calculated are provided in **Table** 6.1.

Table 6.1: DRIFT-Luvuvhu hydrologic and hydraulic input data and indicators

Discipline		Indicator	Units
Hydrology	Annual	Mean annual runoff	m^3/s
	Dry season	Onset	calendar week
		Duration	days
		Minimum 5-day discharge	m^3/s
	Flood season	Onset	calendar week
		Duration	days
		Maximum 5-day discharge	m^3/s
		Average daily volume	$m^3 \times 10^6$
		Volume	
Hydrodynamics	Annual	Number of days flooded	days
	Dry Season	Pan depth	m
		Flooded	nominal
		Shear stress	N/m^2
	Transition Season 1	Shear stress	N/m^2
	Flood season	Pan depth	m
		Flooded	days
		Shear stress	N/m^2
	Transition Season 2	Shear stress	N/m^2

6.4 Indicators

A list of indicators that represent the Luvuvhu River floodplain and the reasons for their selection are shown in **Table** 6.2.

Table 6.2: Wetland indicators and the reasons for their selection

Indicator	Reason for selection	EWR site					
		18	19	20	21	22	23
Hippo pool	A large pool at the junction of the Luvuvhu and Limpopo rivers that supports hippopotami and crocodiles in the dry season.						X
Riparian vegetation	Riparian plants, e.g., marginal reeds and trees, grow on the riverbanks and are habitat for riparian fauna. They also stabilise banks and attenuate floods.	X					X
Floodplain vegetation	Floodplain forests, floodplain shrubs and floodplain grasslands, all variously associated with the floodplain and pans, and all of which provide habitat and food for wildlife.		X	X	X	X	
White-faced duck	Represents dabbling ducks and teals that occur on the pans feeding on seeds, tubers and invertebrates (insects, crustaceans and worms); e.g., the Yellow-billed Duck and the African Black Duck.		X	X*	X	X	
African fish eagle	Represents carnivorous birds that nest in and hunt from tall riparian trees; it eats fish, rodents and other small animals; this group includes the Pied and Malachite Kingfishers.	X	X	X*	X	X	X
Tolerant fish	Fish that are tolerant to a range of flow and water quality variables and are able to persist when trapped in the pans.	X	X	X*	X	X	X
Crocodile	Crocodiles are aquatic reptiles, an apex predator that mostly feed on fish, but take any prey. They need permanent water and sandy banks for nesting.	X	X	X*	X	X	X
Hippopotamus	Hippos are semi-aquatic mammals that need pools deep enough in which to submerge during the day and floodplain grasslands to graze at night.	X	X	X*	X	X	X

6.4.1 Hippo pool

Hippos require water deep enough to submerge in during the day (McCarthy *et al*. 1998) and take refuge in the river if the pans dry. At low water hippos are confined to the river and prefer a water depth of 1 to 2 m to bask (Taylor 2013) and are particularly fond of large, open pools with accessible sand banks in perennial rivers that are used for many years when conditions are favourable (Estes 1992). The indicator "hippo pool" applies to the large pool in the Luvuvhu River upstream of the confluence with the Limpopo River (**Figure** 6-9**)** that is vital at low flows or during droughts during which time the deep sandy pools at the Luvuvhu Limpopo confluence ensure survival.

Figure 6-9: The 'hippo pool' at the confluence of the Luvuvhu (left) and Limpopo (right) Rivers, showing a resident pod of hippos (Photo credit: Vuledzani Thenga, 2023).

The linked indicators, reasons for selection and their relationships with hippo pools are summarised in **Table** 6.3.

Table 6.3: Linked indicators and their relationship with hippo pools

Linked indicator	Reasons	Relationship
Dry, T1, T2, Wet shear stress	Bed sediment scour increases with higher shear stress. (Wilkinson et al. 2004).	Higher shear stress = deeper depth and larger pool volume.

6.4.2 Riparian vegetation

Riparian vegetation comprises in-channel reeds (*Phragmites mauritianus*), which were relatively sparse, and large riparian trees and shrubs (riverine forest). Common trees were *Faidherbia albida, Ficus sycomorus, Xanthocercis zambesiaca, Croton megalobotrys* and *Philenoptera violacea,* although there were also some terrestrial species. The Ana tree, *Faidherbia albida,* was the chosen to represent this community.

It is a tall tree found on the banks of perennial rivers (**Figure** 6-10**)**. It is widely distributed throughout Africa in woodland, wooded grassland and in riverine forest (Moll 1995). It is one of the fastest growing indigenous trees reaching a height of 30 m. It flowers from March to September producing broad, woody, coiled orange seed pods (Curtis and Mannheimer 2005). This tree is deciduous and loses its leaves in summer, thus providing fodder during the winter. The seeds are dispersed in the droppings of the variety of game that graze upon it (www.plantzafrica.com). The trees are drought resistant and can survive water logging and frost for up to 5 days a year (www.plantzafrica.com). The Ana tree responds to increased soil moisture by increasing flowering and seed set (Curtis and Mannheimer 2005).

Figure 6-10: *Faidherbia albida* leaves and woody pods (left) and habit (right)

The linked indicators, reasons for selection and their relationships with riparian vegetation are summarised in **Table** 6.4**.**

Table 6.4: Linked indicators and their relationship with riparian vegetation

Linked indicator	Reasons	Relationship
Dry duration	Riparian vegetation is drought tolerant (www.plantzafrica.com) but will experience desiccation stress over a prolonged dry season. Dry years result in decreased production or even mortality in extreme cases.	A longer dry season = less riparian vegetation.
Dry minimum discharge	The dry season base flow needs to provide enough soil moisture (but not inundation) to ensure survival and persistence during dormancy. There should always be some water in the river.	Lower discharge = less riparian vegetation.
Wet duration	Riparian vegetation grow, flower, fruit and set seed in the wet season. A longer wet season provides more opportunity for growth and reproduction (Curtis and Mannheimer 2005).	A longer wet season = more riparian vegetation.
Wet maximum discharge	The Ana tree responds to increased soil moisture by increasing flowering and seed set (Curtis and Mannheimer 2005). Wet season flows far below the median are likely to retard growth and reproduction.	Lower discharge in the wet season = less riparian vegetation.

6.4.3 Floodplain vegetation

Floodplain vegetation comprises floodplain trees (*Vachellia xanthophloea, Faidherbia albida, Hyphaene coriacea, Combretum imberbe* and *Xanthocercis zambesiaca*), floodplain shrubs (*Maerua parvifolia,* *Gymnosporia senegalensis, Salvadora australis*) and floodplain grasses and sedges (*Sporobolus consimilis, Kyllinga alba* and *Schoenoplectus articulatus*). The leadwood tree, *Combretum imberbe,* was selected as an indicator to represent floodplain vegetation.

Combretum imberbe (**Figure** 6-11) is a woody tree that is desiccation tolerant and can grow just as well in a terrestrial environment (van Wyk and van Wyk 2009). They grow in bushveld and in sand along perennial and ephemeral rivers. It is tolerant of a wide range of soil conditions and flowers from November to February, fruiting all year round but mostly from December to June (Curtis and Manheimer 2005). This species responds to increases in moisture by increasing seed production, such as during rainy periods.

The linked indicators, reasons for selection and their relationships with floodplain vegetation are summarised in **Table** 6.5.

Table 6.5: Linked indicators and their relationship with floodplain vegetation

Linked indicator	Reasons	Relationship
RIVER		
Dry minimum discharge	The link to discharge in the dry season in the Luvuvhu River at its confluence with the Limpopo River is to ensure that stream permanency is 100%, i.e. the Luvuvhu should remain perennial. This is important to maintain shallow depth to groundwater across the floodplain, which is about 2.4 to 6.8 m. Floodplain trees and shrubs are phreatophytic and their survival depends on being able to utilise shallow groundwater, while their recruitment depends on flooding or rainfall events. Maintenance of perenniality in the Luvuvhu River should facilitate maintenance of this shallow depth to groundwater.	Lower discharge in the dry season = fewer floodplain vegetation.
Wet duration	Floodplain vegetation grow, flower, fruit and set seed in the wet season (Curtis and Mannheimer 2005). A longer wet season provides more opportunity for growth and reproduction.	A longer wet season = more floodplain vegetation.
Wet maximum discharge	This link is to wet season flows in the Luvuvhu River at its breach points for flooding of pans and paleochannels. Pans receive flood water from the Luvuvhu when the upstream discharge is about 750 m^3/s (north bank) or 1,000 m^3/s (Wetland Assessment (Volume 2): Hydrodynamic modelling of the Nyl and Luvuvhu Rivers Report).	Discharges that do not overtop the banks do not flood the floodplain = less floodplain vegetation.
PAN		
Dry pan depth Wet pan depth	Water in the pans (especially in the dry season) buffers groundwater levels for the phreatophytic floodplain vegetation.	Less water in the pans = less floodplain vegetation.

Figure 6-11: Floodplain vegetation is represented by *Combretum imberbe*

6.4.4 White-faced duck

While the white-faced duck has been covered in **section 5.4.8** because it is also an indicator for the Nyl floodplain, it is repeated here for ease of access: Adult males of the white-faced duck (*Dendrocygna viduata*; **Figure** 6-12) have a white half front of their head and throat and the rest is black, the wing shoulders are chestnut. The female is similar but has the front of the head and neck spot tinged with rust colour. It does not spend much time perched in trees, rather they prefer dabbling along sand banks (www.krugerpark.co.za).

The white-faced duck is omnivorous and was selected as an indicator to represent other dabbling ducks and teals that occur in backwaters and oxbows on floodplains. It is a social bird that occurs in large flocks (McLachlan and Riversidge 1978) and in large numbers on the Nylsvley floodplain when in flood (www.ramsar.org/ris). They are omnivorous and eat seeds, tubers and invertebrates (insect larvae, insects, worms and crustaceans; McLachlan and Liversidge 1978).

Mutual preening plays an important part in the formation of pairs and maintenance of bonds. Nests are built of leaves on the ground in marshes and in hollow trees (www.krugerpark.co.za) at the end of the dry season from October to November. Clutches consist of 6 to 12 eggs, and both partners incubate the eggs for 28 to 30 days. The ducklings are often hidden in aquatic vegetation by the parents (McLachlan and Riversidge 1978).

The linked indicators, reasons for selection and their relationships with white-faced ducks are summarised in **Table** 6.7.

Table 6.6: Linked indicators and their relationship with white-faced ducks

Linked indicator	Reasons	Relationship
Wet duration	White faced duck hunt in the shallow open water of rivers, lakes and wetlands (McClachlan and Liversidge 1978) which are dependent on the duration of the wet season to remain wet and deep enough.	A longer wet season = more white-faced duck.
Zero days per year	White-faced ducks live in and on permanent water bodies (McClachlan and Liversidge 1978). If the water bodies dry out the ducks will move off to other areas of permanent water.	More zero days = fewer ducks.
Aquatic vegetation	White-faced duck are omnivores eating seeds of aquatic plants, tubers, invertebrates, insects, worms and crustaceans (McLachlan and Liversidge 1978).	More aquatic vegetation = more feeding areas = more ducks.
Reeds	White-faced duck nest and hide their young in marshes (reeds and other graminoids at the water's edge) (www.krugerpark.com).	More reeds = more nesting and hiding places = more ducks.
Coenagrionids	White-faced ducks eat aquatic insects (McLachlan and Liversidge 1978).	More insects = more ducks.

Figure 6-12: White-faced Duck, *Dendrocygna viduata* (Photograph: www.wikipedia.com)

The linked indicators, reasons for selection and their relationships with white-faced duck are summarised in **Table** 6.7.

Table 6.7: Linked indicators and their relationship with white-faced duck

Linked indicator	Reasons	Relationship
Dry pan depth Wet pan depth	White faced duck hunt in the shallow open water of the pans. (McClachlan and Liversidge 1978).	The more open water available the more hunting grounds = more ducks.
Annual days flooded	The longer the pans remain wet the better are the conditions for the ducks.	More days flooded = more ducks.

6.4.5 African fish eagle

The African fish eagle was selected as an indicator to represent carnivorous birds that nest in, and hunt from, perches in woody riparian trees. It primarily eats fish. The giant kingfisher is included in this group.

The African fish eagle (*Haliaeetus vocifer*) has a distinct white head, throat and tail, a chestnut belly, covert underwing and black flight feathers (Ferguson-Lees and Christie 2001). In flight, it appears as a large, broad winged eagle with a short tail. Although sexes are the similar in appearance, females tend to be larger than males (Ferguson-Lees and Christie 2005; **Figure** 6-13). The African fish eagle frequently occurs on large rivers, dams and lakes, and sometimes in estuaries and lagoons. It usually hunts from a perch (Ferguson-Lees and Christie 2001), is primarily dependent on fish but they also eat rats, young birds (young egrets, cormorants, herons) and occasionally carrion. In central Africa, African fish eagles are also reported to kill flamingos (Ferguson-Lees and Christie 2005).

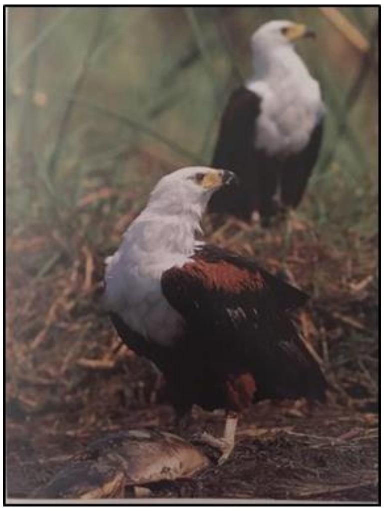

Figure 6-13: African fish eagle, *Haliaeetus vocifer* (Photograph: Sinclair and Davidson 2006)

The linked indicators, reasons for selection and their relationships with African fish eagles are summarised in **Table** 6.8.

Table 6.8: Linked indicators and their relationship with African fish eagles

Linked indicator	Reasons	Relationship
RIVER		
Dry min 5d Q Wet min 5d Q	Fish eagles hunt in the river (Ferguson-Lees and Christie 2005). Higher discharges provide more habitat in which to hunt.	Higher discharge = more fish eagles.
Riparian vegetation	Fish eagles hunt from perches in riparian trees (Ferguson-Lees and Christie 2001) and build nests of sticks high up in the tree (McClachlan and Liversidge 1978).	More riparian vegetation = more fish eagles.
PAN		
Dry pan depth Wet pan depth	Fish eagles hunt in the pans. More water in the pans provides better hunting conditions. (Ferguson-Lees and Christie 2001).	More open water means more hunting grounds = more fish eagles.
Annual days flooded	The longer the pans are full the more time there is for fish eagles to hunt.	More annual days flooded = more fish eagles.

Linked indicator	Reasons	Relationship
Floodplain vegetation	Fish eagles hunt from perches in trees (Ferguson-Lees and Christie 2001) and build nests of sticks high up in s (McClachlan and Liversidge 1978).	More floodplain vegetation = more fish eagles.
RIVER AND PAN		
Tolerant fish	Fish eagles eat fish, but they also eat rats, young birds (young egrets, cormorants, herons) and occasionally carrion (Ferguson-Lees and Christie 2005).	More fish means more food for adults and chicks = more fish eagles.

6.4.6 Tolerant fish

The most widespread fish was *Oreochromis mossambicus* (Mozambique tilapia, **Figure** 6-14) (Malherbe *et al.*, 2017). This fish was chosen as an indicator species because it is a valuable food source for crocodiles and fish eagles. It is a tolerant fish that has a high survival rate in the pans.

Figure 6-14: *Oreochromis mossambicus* juvenile (left, photograph: M Ross) and adult male (right, Skelton, 2001)

Tolerant fish are hardy and adaptable being able to survive a range of flow and water quality conditions. They do not migrate, are omnivorous eating a wide range of food, and thrive at low or slow flow and especially in dams. They tolerate high salinity, a wide range of temperature and low oxygen by breathing from the surface. They eat insects when young and more detritus, phytoplankton, and algae when older. They breed throughout the year. The male builds a nest, and the female broods the eggs on the nest and in her mouth. As the eggs and fry are actively cared for hatching success, survival is high (Skelton 2001).

The linked indicators, reasons for selection and their relationships with tolerant fish are summarised in **Table** 6.9**.**

Table 6.9: Linked indicators and their relationship with tolerant fish.

Linked indicator	Reasons	Relationship
RIVER		
Dry minimum 5d discharge	Tolerant fish persist in the shallow water of the channel in the dry season, but conditions are increasingly stressful at low flow with poorer water quality and increasing competition for resources. Predation also increases as fish concentrate in shallow water.	A longer dry season = fewer tolerant fish.
Wet maximum 5d discharge	Tolerant fish take advantage of the influx of external nutrients and resources as flows increase in the wet season. The improved conditions increase breeding success (Skelton 2001).	A longer the wet season = more tolerant fish.

Linked indicator	Reasons	Relationship
PAN		
Dry pan depth	As the pans dry out and the water levels drop, water quality deteriorates and there is an increase in competition for ever dwindling sources of food. Predation also increases with the concentration of fish in isolated pools.	Shallower pans = fewer tolerant fish.
Wet pan depth	Flooding of the isolated pools during the wet season promotes fish migrations into and out of the pools from the river to maintain genetic diversity. Flooding also flushes sediments and other accumulated contaminants and nutrients from the pools and replenishes them with cleaner water.	Deeper pools = more tolerant fish.
Annual days flooded	The longer the pans remain inundated the more habitat there is for tolerant fish.	More annual days flooded = more tolerant fish.
RIVER AND PAN		
Crocodiles	Crocodiles eat fish. The greater the number and concentration of crocodiles associated with an isolated pool, the greater the impact to the resident fish that cannot escape. But the total absence of crocodiles will promote the proliferation of the fish to the point where population numbers deplete the isolated system of resources, causing a population crash.	More crocodiles = fewer tolerant fish.

6.4.7 Crocodiles

The information relating to crocodiles (**Figure** 6-15) was obtained from Combrink (2004).

Young Nile crocodiles hatch from hard shelled eggs and are usually carried by their mothers to nearby sheltered waters where they are guarded for up to two months. They then become independent and at 1.2 m in length are solitary in nature until they reach maturity at 2.5 m in females and 3 m in males. Mating takes place in shallow water during July and August. In the early breeding season males attract females by displaying mating behaviour and vocalisation. At night, females excavate nests, 30 to 45 cm deep, in loose soil/sand and lay 16 to 80 white hard shelled eggs, 2 months after mating. The young hatch after being incubated by the mother for three months and are removed from the nest by the mother. The young stay together in a “crèche” for 6-8 weeks during which time the mother often remains among them and will violently attack any potential threat.

Figure 6-15: A Nile crocodile taken at Crookes Corner (Photo credit: Christine MacKenzie, 2023)

Once the young leave the “crèche” the juvenile crocodiles often dig a burrow up to 3 m long and spend much of the first 4 to 5 years of their life in or near the burrow. Initially the growth rate is about 30 cm per year up to 1.2 m in length and then slows to about 2.5 cm per year. After the hatchling period the juveniles spread out into the shoreline vegetation, backwaters and inlets. When they are sexually mature males develop a dominance hierarchy at the start of the breeding season (May). They will mate with females who will then seek out a suitable nesting area to dig their nest, usually in November.

Juveniles tend to eat larger prey and this includes fish, crabs, terrapins, reptiles and birds. As they grow larger crocodiles eat progressively larger prey, such as catfish, water monitors and mammals. Carrion will also be eaten as will domestic stock (cattle and goats).

The linked indicators, reasons for selection and their relationships with crocodiles are summarised in **Table** 6.10**.**

Table 6.10: Linked indicators and their relationship with crocodiles

Linked indicator	Reasons	Relationship
RIVER		
Dry minimum 5-day discharge	Crocodiles hunt fish and other prey in the river (Combrink 2004). Higher discharge provides more cover and better conditions for hunting.	Higher discharge in the dry season = more crocodiles.
Wet maximum 5-day discharge		Higher discharge in the wet season = more crocodiles.
PAN		
Dry pan depth	As the pans dry out and the water levels drop, water quality deteriorates and there is an increase in competition for ever dwindling fish. It is increasingly difficult to hunt in shallower water.	Shallower pans = fewer crocodiles.
Wet pan depth	Flooding of the isolated pools during the wet season promotes fish migrations into and out of the pools from river	Deeper pools = more crocodiles.

Linked indicator	Reasons	Relationship
	to maintain genetic diversity. Replenished water levels provide more cover and better conditions for hunting.	
RIVER AND PAN		
Tolerant fish	Crocodiles eat fish (Combrink 2005) so more fish provide more food to support more crocodiles and promotes better growing conditions.	More fish = more crocodiles.

6.4.8 Hippopotami

Hippopotami (*Hippopotamus amphibius*) are large, mostly herbivorous, semi-aquatic mammals native to sub-Saharan Africa (**Figure** 6-16). They have recognisable barrel-shaped torsos, wide open mouths with large canine tusks, hairless bodies and stumpy legs (Bothma and du Toit 2010).

The Hippo was selected as an indicator because it is a semi-aquatic herbivore whose life history is intimately tied to seasonal changes in flow and flooding of the floodplain. At low water they are confined to the river and prefer a water depth of 1 to 2 m to bask (Taylor 2013). They prefer permanent, open water in which they can submerge, such as pools or rivers with banks that slope gradually (McCarthy *et al*. 1998). They are particularly fond of large, open pools with accessible sand banks in perennial rivers that are used for many years when conditions are favourable (Estes 1992). They sometimes move up and down the river when it is in flood but return to original pools when floods recede. They make use of the same trails beneath the surface of the water (in lakes/backwaters) to reduce erosion that would reduce visibility as they move (McCarthy *et al*. 1998). This also reduces their energy spent moving through submerged and emergent aquatic plants; they maintain the same paths to keep them open (Kamweneshe *et al*. 2002).

They graze grasses and sedges on the floodplain but sometimes eat floating aquatic plants (Estes 1992). Hippos graze on land at night travelling 2 to 5 km from the shoreline and up to 20 km in search of suitable grazing during droughts (Lewison and Carter 2004). They use the same paths repeatedly to access their grazing areas (Klinger H. 1991; Lock 1972, cited by McCarthy *et al*. 1998). Their search for food influences the geomorphology of large wetland systems, maintaining pathways and developing new channel systems that enhances water movement and leads to the expansion of the wetland (McCarthy *et al*. 1998).

Hippos breed throughout the year, with a peak from October to March that may be related to rainfall (Estes 1992). The gestation period varies from 225 to 257 days. When a cow is ready to give birth, she separates herself from the herd to give birth in shallow water near the river bank or elsewhere depending on the season since young are born at any time of the year (Sheppe and Osbourne 1971). A calf will remain with the cow until it reaches maturity at 6–8 years of age (de Magalhaes and Costa 2009). The calving interval is 22 months, which means that a cow calves once every 2.5 years (Bothma and du Toit 2010).

Figure 6-16: Hippopotami, *Hippopotamus amphibious* at the 23_Luvuvhu3 site (Photograph credit: Vuledzani Thenga, 2023)

The linked indicators, reasons for selection and their relationships with Hippopotami are summarised in **Table** 6.11.

Table 6.11: Linked indicators and their relationship with Hippopotami

Linked indicator	Reasons	Relationship
RIVER		
Dry duration	Hippos are confined to shallow pools in the river during the dry season, preferring depths of 1 to 2 m in which to bask (Taylor 2013). They prefer permanent, open water in which can submerge (McCarthy *et al*. 1998).	A longer dry season = more stressful conditions for the hippos.
Dry min 5d Q		Lower discharge in the dry season = fewer pools = more stressful conditions.
Wet max 5d Q	They are particularly fond of large, open pools with accessible sand banks in perennial rivers that are used for many years when conditions are favourable (Estes 1992). They sometimes move up and down the river when it is in flood but return to original pools when floods recede.	Higher discharge in the wet season = more hippos.
Hippo pools	A large pool at the confluence of the Luvuvhu and Limpopo rivers that is maintained by Luvuvhu River flows and supports hippos in the dry season.	A reduction in the depth and size of this pool = more stressful conditions for the hippos.
PAN		
Dry pan depth	Hippos spend the day submerged in pans that are deep enough (McCarthy *et al*. 1998). During droughts, if a pan becomes too shallow, hippos move to the Luvuvhu River (Sandra Visagie, pers.com.).	Deeper pans = more hippopotami.
Wet pan depth	Hippos spend the day submerged in pans that are deep enough, and in the wet season this is important to maintain safety and security of the herd (McCarthy *et al*. 1998).	
Floodplain vegetation	Hippos feed on floodplain sedges and grasses (Lewison and Carter 2004) and may venture ≤8 km from the pan (Estes 1992) to forage at night.	More floodplain vegetation = more hippopotami.

6.5 Present Ecological status

The Present Ecological Status (PES) of the Luvuvhu River floodplain was determined using the WET-Health Level 1 (Macfarlane *et al*. 2007) assessment method that generates an Ecological Category for Hydrology, Geomorphology, Water quality and Vegetation. The PES for the animal indicators was derived from a combination of two or three of the floodplain driver scores (as appropriate) and adjusted based on other available information (local knowledge, literature, data) and observations in the field if necessary.

The vegetation module score was 87%, a B category (Wetland Assessment Volume 1 – Ecostatus and Priority Wetlands). The rating, reasons and results are shown in **Table** 6.12**.**

Table 6.12: Vegetation module (WetHealth Level 1; Macfarlane *et al*. 2007) for the Luvuvhu River floodplain

Disturbance Class	Extent (%)	Typical intensity	Intensity (0 – 10)	Magnitude	Additional Notes	Confidence rating
Infrastructure	3	10	10	0.3	Gravel and tar roads, airstrip	High
Deep flooding by dams	0	10	10	0.0		
Shallow flooding by dams	0	4 – 8	6	0.0		
Crop lands	0	8 – 10	9	0.0		
Commercial plantations	0	7 – 10	9	0.0		
Annual pastures	0	9 –10	9	0.0		
Perennial pastures	0	4 – 10	8	0.0		
Dense alien vegetation patches.	5	5 – 10	7	0.4	No dense patches but AIP are present and there's a fulltime team constantly busy with removal	High
Sports fields	0	7 – 10	9	0.0		
Gardens	0	6 – 10	8	0.0		
Areas of sediment deposition/ infilling and excavation	1	4 – 10	8	0.1	Raised road from bridge over the Luvuvhu across the floodplain	High
Eroded areas	0	3 – 9	7	0.0		
Old / abandoned lands (Recent)	0	7 – 9	7	0.0		
Old / abandoned lands (Old)	0	3 – 8	5	0.0		
Overgrazing	20	1 – 5	3	0.6	Contentious, but the floodplain is heavily utilised and damage by elephants, which is extensive and notable.	High
Untransformed areas	0	0 – 3	1	0.0		
Overall weighted impact score				1.3		
Vegetation PES% Score				87%		
Vegetation PES Category				**B**		

The overall PES for the Luvuvhu River floodplain is 80%, a **B/C** category (**Table** 6.13). The primary drivers of change were an altered flow regime, invasive alien plant species and pressure from megaherbivores.

Table 6.13: Overall PES for the Luvuvhu River floodplain (WET-Health 1)

Components	Method used for assessment	PES% Score	Ecological Category
Hydrology PES	WET-Health Hydrology Module	70 %	C
Geomorphology PES	WET-Health Geomorphology Module	90 %	A/B
Water quality PES	Wetland-IHI Water Quality Module	71 %	C
Vegetation PES	WET-Health Vegetation Module	87 %	B
Overall Wetland PES	WET-Health default weightings	80 %	**B/C**

Tolerant fish are found in the river and in the pans and were given a B/C category from the combination of drivers that control the quality of their habitat; hydrology, water quality and geomorphology (**Table** 6.14**)**.

Birds are in a B/C category because white-faced ducks were assigned a B/C, from the combination of scores for hydrology, water quality and vegetation that influence their open water and riparian habitats, and African fish eagles a B/C from the combined scores of hydrology and vegetation, because they hunt in open water and roost and nest in trees on the river banks and floodplain.

Wildlife was assigned a B category from the combination of a B/C category for hippopotami that resulted from combining the scores for hydrology, water quality and vegetation, and a B for crocodiles that resulted from combining scores for hydrology, geomorphology, water quality and fish. Hippo census data for the Luvuvhu River floodplain shows a stable and increasing population (Eddie Riddell 2024 pers. Com.).

The scores for biota were kindly reviewed by Eddie Riddell and Richard Sowry.

Table 6.14: Derived scores for biota on the Luvuvhu River floodplain

<table>
<tr><th>Discipline</th><th>Indicator in DRIFT</th><th>WET-Health drivers combined</th><th colspan="2">Ecological category</th></tr>
<tr><td>Fish</td><td>Tolerant fish</td><td>Hydrology (C), geomorphology (A/B), water quality (C)</td><td colspan="2">B/C</td></tr>
<tr><td rowspan="2">Birds</td><td>White-faced duck</td><td>Hydrology (C), water quality (C), vegetation (B/C)</td><td>B/C</td><td rowspan="2">B/C</td></tr>
<tr><td>African fish eagle</td><td>Vegetation (B), fish (B/C)</td><td>B/C</td></tr>
<tr><td rowspan="2">Wildlife</td><td>Hippopotami</td><td>Hydrology (C), water quality (C), vegetation (B)</td><td>B/C</td><td rowspan="2">B</td></tr>
<tr><td>Crocodiles</td><td>Hydrology (C), geomorphology (A/B), water quality (C), fish (B/C)</td><td>B</td></tr>
</table>

6.6 Description of scenarios

The hydrological modelling for the rivers component of this study (River Assessment (Volume 2): Data Collection and Analysis Report) was extended to provide hydrological time-series for Naturalised and PES flow scenarios at a daily time-step for the period 1925 to 2021 for the lower Luvuvhu River. This required combing the extrapolated daily discharge time-series for the river EWR sites 12_Luvuvhu upstream of the Luvuvhu River floodplain (using a catchment area factor of 1.366) and its incremental tributary on the Mutale River, 14_Mutale2. Since hydrological modelling of the Limpopo River was not part of this study (**Section 1.4**) monthly time-series data were obtained from the LIMCOM study (O'Brien *et al.* 2022) that extend from 1925 to 2011. Since all the hydrological inputs into DRIFT-Luvuvhu must be at the same time-step and for the same period it was necessary to shorten the Luvuvhu River hydrological record by ten years from 2021 to 2011 and to disaggregate the monthly flows for the Limpopo River to a daily time-step. Gauged flow data are available for the Limpopo River after 1955 from the DWS hydrometric station at Beit Bridge (A7H004/8), located ~158 km upstream of the Luvuvhu River confluence. These records were infilled for missing periods and used to disaggregate the modelled monthly volumes to provide a 56-year concatenated daily time-series (Naturalised and PES) from 1955 to 2011.

The four scenarios assessed at the two river EWR sites were loaded into DRIFT-Luvuvhu:

- PES (2022), which used the climatic period of 1955-2011 with human influences such as water-resource developments, population and land use at 2022 levels.
- Naturalised, which used the climatic period of 1955-2011 with human influences such as water-resource developments, population and land use at *c*. 1900 levels.
- Future1, which overlaid 2050 water resource developments on PES.
- Future2, which overlaid a dry future climate scenario onto Future1.

These scenarios changed flows in the Luvuvhu River but since flooding of the floodplain is controlled by a combination of flows in the Luvuvhu and Limpopo Rivers, and there was no consideration of future developments in the Limpopo River[72], their effect on the pans was muted.

DRIFT-Luvuvhu was calibrated against the PES and Naturalised scenarios. The Future1 and Future2 scenarios were then run through the DRIFT-Luvuvhu to predict the effects of additional planned water-resource development without and with a dry climate, respectively.

The factors considered in the Future1 scenario (**Table** 6.15) included raising existing dams or building new dams (increased storage), decreasing releases from dams because of increasing demands and increasing domestic or agricultural water use. The consequences of these developments at 18_Luvuvhu2 are a combination of the consequences in the Luvuvhu and the Mutale Rivers (**Table** 6.16). The Luvuvhu experiences reduced wet season flows because of the increased demand from Nandoni Dam on the Luvuvhu River that results in fewer wet season spills and lower dry season flows because Nandoni cannot meet all the required releases. In the Mutale there are major reductions all year round because of the building of Rambuḓa Dam on the Mutale River with increased demand from the river.

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[72] There are two flow scenarios available from the Limpopo River from the ongoing LIMCOM study (O'Brien 2022), Baseline and Naturalised.

Table 6.15: Factors relevant for the Future1 scenario on rivers applicable to the Luvuvhu River floodplain

EWR site	Increased return flows	Increased dam storage	Increased dam releases	Transfers of return flows out of the catchment	Incoming inter-basin transfers	Increased water use
12_Luvuvhu	X			X		X
14_Mutale2		X				X

Table 6.16: Monthly flows in the PES and Future1 scenarios (Mm^3/a, incremental inflows to the Luvuvhu River floodplain)

Scenario	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
12_Luvuvhu													
PES	1.60	4.35	15.92	44.68	75.56	60.90	25.76	8.19	4.41	2.87	1.96	1.56	247.8
Future1	1.30	3.00	10.23	29.78	61.68	51.44	21.06	6.27	3.52	2.44	1.87	1.43	194.0
14_Mutale2													
PES	2.54	6.03	14.40	27.92	40.66	28.39	12.22	4.26	2.23	1.97	1.51	1.51	143.6
Future1	0.80	3.03	10.70	25.08	38.48	26.05	10.14	2.55	0.99	0.70	0.58	0.53	119.6

6.6.1 Ecologically relevant flow indicators

Median values for the ecologically relevant flow indicators at the two river sites, and average[73] values at the pans, are provided in **Table** 6.17. The ecologically relevant flow indicators that best described the differences between scenarios for the two river sites are Mean Annual Runoff; discharge, volumes, duration and onset of the dry and wet seasons, and in the pans are depth and number of days flooded annually.

The flow regime of the Naturalised scenario is wetter than PES at all sites while Future1 is dryer than PES and Future2 is dryer than Future1. The river sites (18_Luvuvhu2 and 23_Luvuvhu3) are however more influenced by scenarios than pans (19_Nwambi, 20_Mambvumbvanyi, 21_Hapi, 22_Tlangelani) with pan depth appearing fairly resilient across Future scenarios compared to PES.

Table 6.17: Ecologically-relevant flow indicators in DRIFT-Luvuvhu

Scenario	PES (2022)	Naturalised	Future1	Future2
18_Luvuvhu2 (median values)				
Mean annual runoff	7.93	14.32	4.43	2.57
Dry minimum 5-day discharge	0.58	3.09	0.27	0.12
Dry duration	230.50	176.00	239.00	271.00
Dry onset	17.00	22.00	18.00	15.00
Wet maximumax 5-day discharge	69.26	110.92	40.70	21.94
Wet duration	90.00	171.00	78.00	60.00
Wet onset	45.00	44.00	10.00	9.00
Wet season volume	155.33	305.25	68.18	24.42

[73] Averages were better suited to the pan flow indicators because the median values were zero in many cases as the pans are not perennial.

Scenario	PES (2022)	Naturalised	Future1	Future2
Wet average daily volume	2.27	2.14	1.70	1.17
19_Nwambi (average values)				
Dry: Pan depth	0.6	1.0	0.5	0.5
Wet: Pan depth	0.8	1.4	0.8	0.7
Dry: Flooded	0.2	0.4	0.2	0.2
Wet: Flooded	0.3	0.4	0.3	0.2
Annual: Days flooded	91.5	133.6	84.6	60.5
20_Mambvumbvanyi (average values)				
Dry: Pan depth	0.2	0.2	0.2	0.2
Wet: Pan depth	0.6	0.8	0.6	0.6
Dry: Flooded	0.0	0.1	0.0	0.0
Wet: Flooded	0.1	0.2	0.1	0.1
Annual: Days flooded	28.9	43.4	26.8	18.6
21_Hapi (average values)				
Dry: Pan depth	0.6	0.6	0.6	0.6
Wet: Pan depth	0.8	0.9	0.8	0.8
Dry: Flooded	0.2	0.2	0.2	0.2
Wet: Flooded	0.4	0.4	0.4	0.4
Annual: Days flooded	87.6	89.1	87.6	87.6
22_Tlangelani (average values)				
Dry: Pan depth	0.7	0.7	0.7	0.7
Wet: Pan depth	1.2	1.2	1.2	1.2
Dry: Flooded	0.2	0.2	0.2	0.2
Wet: Flooded	0.3	0.3	0.3	0.3
Annual: Days flooded	84.5	84.6	82.8	82.0
23_Luvuvhu3 (median values)				
Mean annual runoff	7.933	14.318	4.430	2.574
Dry minimum 5-day discharge	0.577	3.093	0.274	0.119
Dry duration	230.500	176.000	239.000	271.000
Dry onset	17.000	22.000	18.000	15.000
Wet maximumax 5-day discharge	69.256	110.916	40.703	21.945
Wet duration	90.000	171.000	78.000	60.000
Wet onset	45.000	44.000	10.000	9.000
Wet season volume	155.327	305.247	68.177	24.424
Wet average daily volume	2.265	2.141	1.699	1.175

6.7 Outcomes of the scenario analyses

The outcomes of the four flow scenarios (**Figure** 6-17) are summarised as daily time series for the riverine biota (**Section 6.7.1**), percentage changes in median abundance relative to PES (**Section 6.7.2**) and on the overall ecological condition (**Section 6.7.3**).

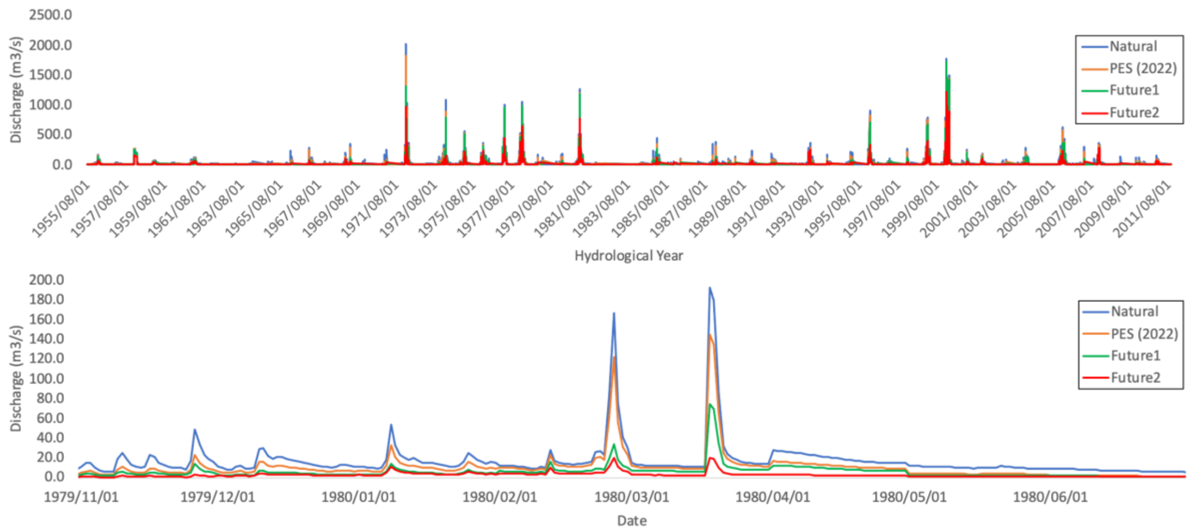

Figure 6-17: Daily discharge time-series (top) and zoomed in on one year (bottom) of the four scenarios used in DRIFT

6.7.1 Time series of responses

The graphs show predicted changes in the indicators as changes in percentage relative to PES (2022).

The responses of riparian and floodplain vegetation are shown in **Figure** 6-18. Both floodplain and riparian vegetation are more abundant in the Naturalised flow scenario and expected to be negatively affected by the planned developments in Future1 and further by climate change in the Future2 flow scenario. While floodplain and riparian vegetation have similar temporal responses floodplain vegetation appears more resilient to change. The response of vegetation to dryer (droughts of the 80s and early 90s) and wetter periods (early 2000s) is well captured in modelling outputs. The timeframe of recovery periods seems uninfluenced by the type of scenario.

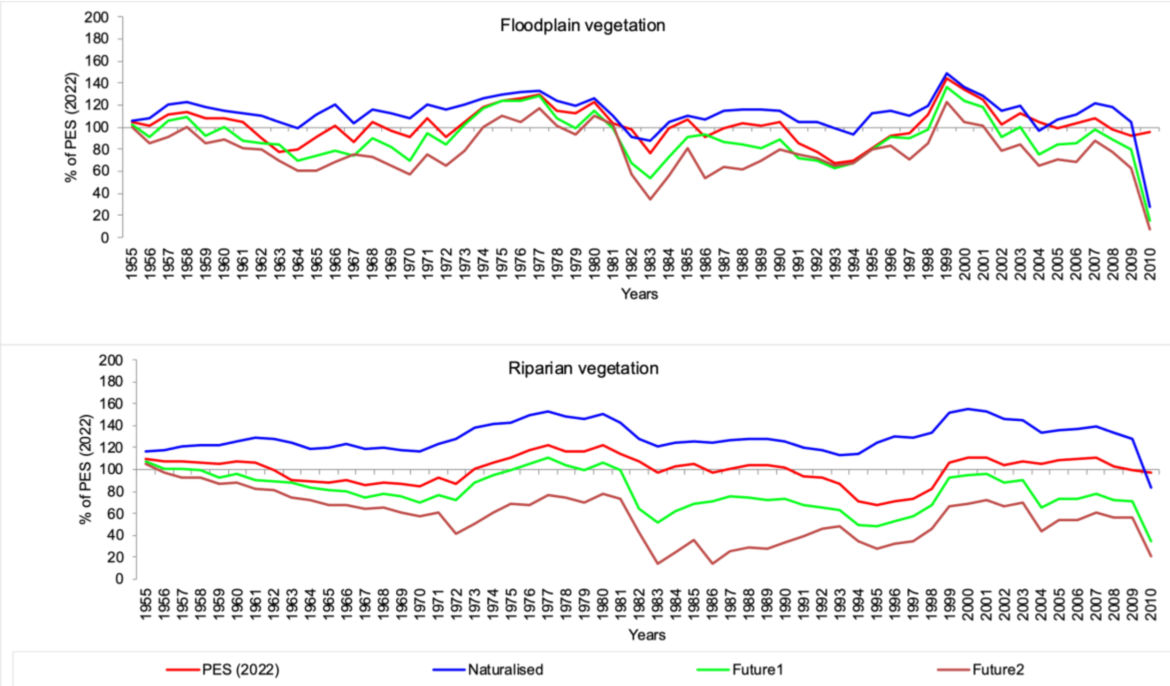

Figure 6-18: Changes predicted in the abundance of riparian (top) and floodplain (bottom) vegetation relative to PES

Tolerant fish changed little in response to the Naturalised, Future1 and Future2 flow scenarios (**Figure** 6-19**)**. Their resilience was in response to their strong links with pan depth, which were not influenced heavily by the flow scenarios (**Table** 6.17**)**.

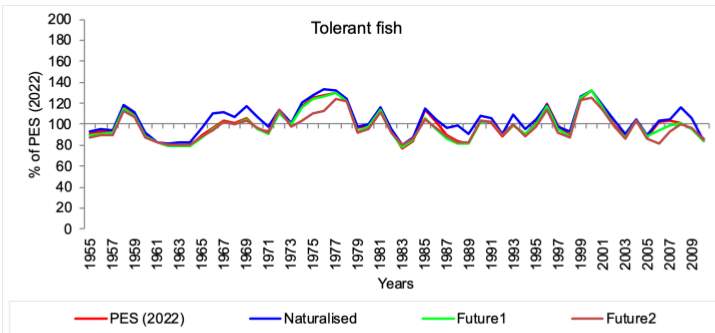

Figure 6-19: Changes predicted in the abundance of tolerant fish relative to PES

White-faced ducks were more resilient to change than African fish eagles (**Figure** 6-20). African fish eagles are more strongly linked to riparian and floodplain trees in which they perch and nest, which are expected to change more than pan depth that is more resilient to changes and to which white-faced ducks are linked.

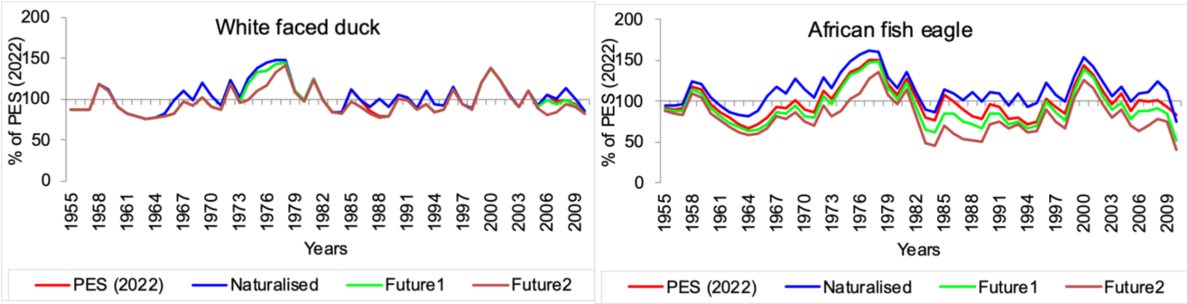

Figure 6-20: Changes predicted in the abundance of water birds relative to PES

Hippopotami were expected to be more responsive to changes in the flow scenarios because they are more sensitive to changes in water depth (of pools in the river and the pans) than crocodiles, and while pan depth did not change much, the depth of the large hippo pool at the junction of the Luvuvhu and Limpopo Rivers that acts as a refuge for the animals during droughts was more sensitive to change (**Figure** 6-21).

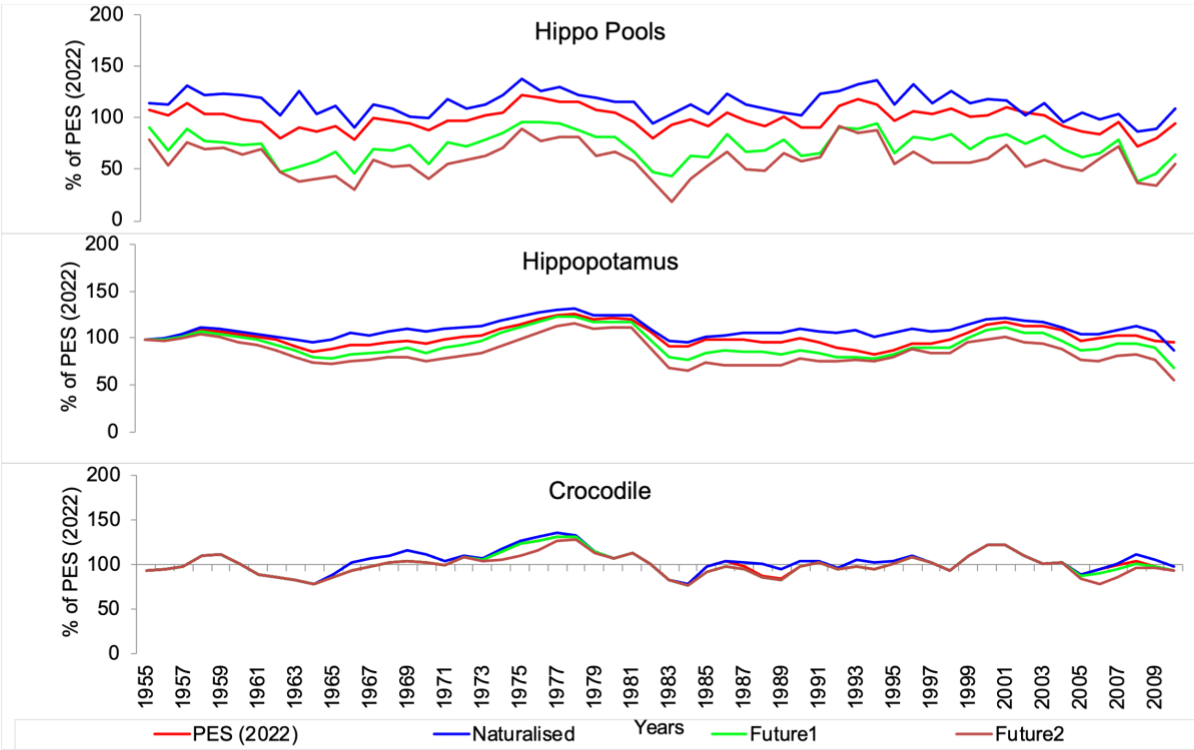

Figure 6-21: Changes predicted in the abundance of hippo pools, hippopotami and crocodiles relative to PES

6.7.2 Mean percentage changes in abundance of habitat and riverine biota

The outcomes of the flow scenarios on the overall abundance in the indicators are shown in **Table** 6.18. Warm colours indicate reductions in abundance relative to PES and cool colours increases. The main responses predicted were for:

- Reductions in the abundance of riparian vegetation, African fish eagles and hippopotami at 18_Luvuvhu2 in response to the future developments planned in the Future1 flow scenario, which were more severe under climate change in Future2.
- Reductions in the abundance of floodplain vegetation at the four pans in Future1, which were more severe in Future2.
- Reductions in the abundance of hippo pools, riparian vegetation, African fish eagles, hippopotami and crocodiles at 23_Luvuvhu3, which are more severe in Future2.

Table 6.18: Mean percentage changes in riverine biota relative to PES

Riverine biota	PES (2022)	Naturalised	Future1	Future2
18_Luvuvhu2				
Riparian vegetation	-0.2	30.4	-19.3	-41.6
Tolerant fish	-1.6	8.9	-3.0	-5.9
African fish eagle	-1.8	20.9	-11.9	-28.2
Crocodile	-0.9	14.3	-9.5	-19.5
Hippopotamus	0.8	11.8	-15.9	-33.7
19_Nwambi				
Floodplain vegetation	1.8	10.9	-10.7	-22.0
Tolerant fish	0.7	7.6	-1.2	-5.6
White faced duck	1.0	8.3	-1.4	-6.0
African fish eagle	0.4	16.1	-5.2	-16.1
Crocodile	0.4	5.5	-0.9	-3.7
Hippopotamus	1.6	8.0	-2.8	-7.2
20_Mambvumbvanyi				
Floodplain vegetation	-0.5	10.1	-10.3	-21.3
Tolerant fish	-0.8	3.2	-0.4	-2.1
White faced duck	-1.2	4.2	-0.5	-3.1
African fish eagle	-0.2	8.7	-3.7	-10.3
Crocodile	0.0	3.5	-0.4	-2.4
Hippopotamus	-0.3	8.4	-2.4	-7.1
21_Hapi				
Floodplain vegetation	0.3	8.6	-10.2	-20.4
Tolerant fish	0.5	0.4	0.0	0.0
White faced duck	0.1	0.7	0.0	0.0
African fish eagle	-1.6	3.5	-2.9	-6.1
Crocodile	1.5	0.3	0.0	0.0
Hippopotamus	0.6	2.0	-1.2	-2.6
22_Tlangelani				
Floodplain vegetation	0.3	8.6	-10.2	-20.4
Tolerant fish	0.5	0.4	0.0	0.0
White faced duck	-0.2	0.0	-0.6	-0.9
African fish eagle	1.0	2.6	-3.9	-7.5
Crocodile	1.5	0.3	0.0	0.0
Hippopotamus	0.6	2.0	-1.2	-2.6
23_Luvuvhu3				
Hippo Pools	-0.6	10.5	-19.4	-28.4

Riverine biota	PES (2022)	Naturalised	Future1	Future2
18_Luvuvhu2				
Riparian vegetation	-0.5	27.9	-17.7	-37.9
Tolerant fish	-0.7	8.5	-3.4	-6.4
African fish eagle	-0.6	19.6	-11.3	-25.9
Crocodile	-0.8	14.3	-9.9	-20.0
Hippopotamus	0.8	13.1	-19.2	-38.6

6.7.3 Overall ecosystem integrity

The overall integrity of the Luvuvhu River floodplain is expected to drop from a B/C category under the PES scenario to a C under the Future1 flow scenario and a C/D under Future2 (**Figure** 6-22**)**. The changes in each discipline are shown in **Table** 6.19 that shows vegetation dropping one full category from a B to a C under Future1, fish remaining the same, and birds and wildlife dropping a half category each from a B/C to a C category (**Table** 6.19).

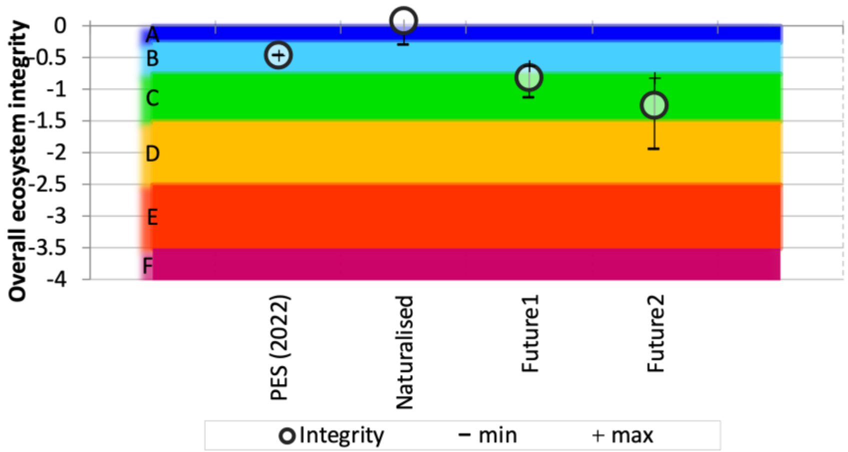

Figure 6-22: The overall ecosystem integrity of the Luvuvhu River floodplain under the four flow scenarios

Table 6.19: Changes predicted in the ecological category of each discipline under the four scenarios

	PES (2022)	Naturalised	Future1	Future2
Vegetation	B	A	C	D
Fish	B/C	B	B/C	C
Birds	B/C	A	C	C/D
Wildlife	B	A	B/C	C
Overall	B/C	A	C	C/D

6.8 Hydrodynamic functioning and EWRs

The Luvuvhu River is ~18 km long from Lanner Gorge to its confluence with the Limpopo River. Over this distance, the river drops 10 m in elevation to where the floodplain is located. The floodplain varies in width and complexity and comprises several flood channels on both banks with channel features and depressions that form pans in a range of sizes, depths and perenniality. Those on the northern (left) bank are more complex than on those on the southern (right) bank. The floodplain ecosystem is driven by, and dependent on, the flooding regime of the Luvuvhu and Limpopo rivers, and the vast floodplain forests of phreatophytic plants that depend on groundwater during the dry season.

The floodplain is inundated by bank overtopping in the Luvuvhu River, backfilling from the Limpopo and Luvuvhu rivers and direct input from rainfall and associated overland runoff. These sources can act in tandem or in complicated combinations, thereby creating high variability, both spatially and temporally, of flooding. A conceptual understanding of flow paths over the floodplain from these three sources is presented in **section 4.2.5.2** and outlined in **Figure** 4.28.

Flooding of the Luvuvhu River floodplain and its pans (as well as the whole Makuleke system of wetlands) has numerous important functions:

- Initiation of dynamic ecological processes and interactions among a wide range of species
- Promotion of biodiversity - the key driver for biological processes and subsequent high biodiversity on the floodplain is the lateral connectivity to the river of the floodplain wetland
- Shifting of sediments (erosion and deposition) and creation of floodplain features/topography
- Delivering sediment, organic matter and nutrients to the floodplain
- Improving water quality in pans by flushing
- Increasing pan depth for hippos, crocodiles, fish and birds
- Creation of recruitment opportunities for floodplain biota including riparian and floodplain forest vegetation
- Germination of seeds or tubers of aquatic macrophytes
- Recharging of the groundwater that maintain shallow depths to groundwater which is important for phreatophytes in the dry season
- Initiation of growth and reproduction of floodplain phreatophytes
- Stimulation of growth and reproduction of aquatic macroinvertebrates
- Cueing of burrowing or dormant amphibians to emerge, feed and reproduce
- Cueing of migration and breeding of fish

- Informing water birds that food, in the form of macroinvertebrates, frogs and fish, is on the increase and breeding habitats (aquatic plants, floodplain vegetation) are being refreshed.

The EWRs are separated into floods and low flows. The floods are derived from the PES flood requirements that inundate the floodplain and fill the pans. A description of the low flows to maintain perenniality of the Luvuvhu River are derived from the PES and Future1 flow scenarios, the former for use prior to development and the latter post-development.

6.8.1 PES floods that inundate the floodplain and fill the pans

The Luvuvhu River floodplain floods in three ways:

- the Luvuvhu River breaching its banks and depending on the size of the flood may flood one or several of the pans
- back flooding in an upstream direction when the Limpopo River floods and pushes up the Luvuvhu River
- direct input from rainfall and smaller catchment and tributary flows during rain events.

The three of these options may occur in any combination, which adds to the complexity of the flooding characteristics. The PES return periods for filling the four EWR pan sites are given in (**Table** 6.20). The maximum discharge in the Luvuvhu River required for pan infilling (from overtopping the levees), or the combination of flows in the Luvuvhu and Limpopo Rivers for pan backfilling (from the Limpopo backing up the Luvuvhu River), are given in **Table** 6.21.

Table 6.20: Return periods of pan filling from overtopping of the Luvuvhu (levee breach) or backfilling from the Limpopo River (from 1995 to 2011)

Pan	Source	Return period
Nwambi/ Mambvumbvanyi	Luvuvhu River breaches levees	7.0
	Limpopo River backs up	4.7
Hapi	Luvuvhu River breaches levees	18.7
	Limpopo River backs up	na
Tlangelani	Luvuvhu River breaches levees	6.2
	Limpopo River backs up	14.0

Table 6.21: The maximum discharge (m^3/s) when pans were flooded[74] and source of flooding; inflow (Luvuvhu River) or backfill (Luvuvhu and Limpopo Rivers)

Year	Nwambi			Mambvumbvanyi			Hapi			Tlangelani		
	Inflow	Backfill		Inflow	Backfill		Inflow	Backfill		Inflow	Backfill	
	Luv	Luv	Lim	Luv	Luv	Lim	Luv	Luv	Lim	Luv	Luv	Lim
1958		266	4 191		266	4 191					266	4 191
1972	1 817	1 817	2 580	1817	1817	2 580	1817			1817	1817	2 580
1974	894	894	573	894	894	573				894	894	
1975		525	2 593		525	2 593						
1977	960	960	1 708	960	960	1 708				960	960	
1978	995	995	1 305	995	995	1 305				995	995	
1981	1 204	1204	1 395	1 204	1 204	1 395	1204			1204	1 204	
1985		352	1 299		352	1 299					352	
1996	831	831	4 441	831	831	4 441				831	831	4 441
1999	752	752	448	752	752	448				752	752	
2000	1 722	1722	13 636	1 722	1 722	13 636	1 722			1 722	1 722	13 636
2006		575	994		575	994				575	575	
Min*			994			994				575		4 191
Min	752	266	448	752	266	448	1 204		0	575	266	2 580
Average**	1 147	908	2 930	1 147	908	2 930	1 581		n/a	1 083	943	6 212

*Min when rivers not flooding together
**Excludes 2000 outlier in Limpopo

Using the Nwambi and Mambvumbvanyi as examples, the Luvuvhu River overtops the floodplain levees to flood the floodplain on average once every seven years. This is reduced to once every ~five years when backfilling from a combination of floods in the Limpopo and Luvuvhu Rivers is also considered (**Table** 6.20). The minimum discharge in the Luvuvhu River that breaches the levees is 752 m^3/s and the average is 1 147 m^3/s (**Table** 6.21).

The Hapi Pan floods once every ~19 years (infilling only (**Table** 6.20) at a minimum of 1 204 m^3/s and an average of 1 581 m^3/s in the Luvuvhu River (**Table** 6.21) and does not backfill.

Tlangelani Pan floods once every six years (**Table** 6.20) when flows in the Luvuvhu River overtop the levees (**Table** 6.21) and once ~14 years when floods in the Limpopo River backup into the Luvuvhu River. The minimum discharge in the Luvuvhu River that breaches the levees is 575 m^3/s and the average is 1 083 m^3/s (**Table** 6.21).

The combinations of discharge in the Luvuvhu and Limpopo Rivers that breach the levees and flood the floodplains to fill the Nwambi, Mambvumbvanyi, Hapi and Tlangelani pans are summarised in **Figure** 6-23. The graphs show the relationship between discharge in the Luvuvhu and Limpopo Rivers that result in backfilling of pans (red line), as well as discharge required in the Luvuvhu River only for infilling (blue line). The red line shows a higher discharge in the Limpopo River can flood the floodplain and backfill the pans when flows are low in the Luvuvhu River, or that lower flows in the Limpopo River need

[74] These are maximum discharge values from the timeseries of the applicable year and may therefore be higher than the actual discharge required for pan filling.

a higher discharge in the Luvuvhu for the same result. A similar but different relationship for the Tlangelani pan is also shown.

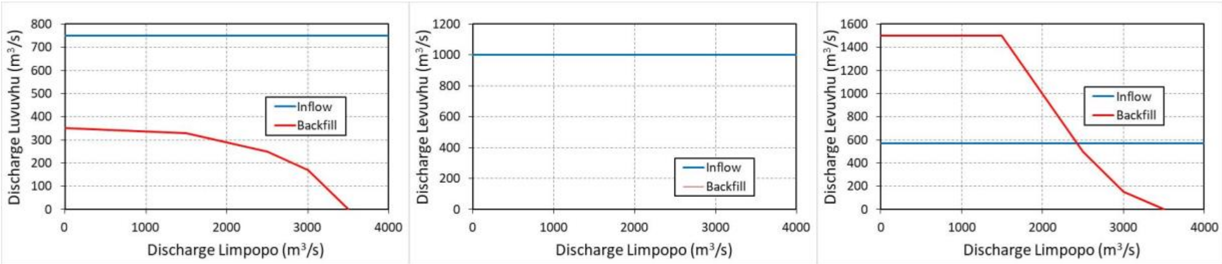

Figure 6-23: Modelled relationships of inflow and backfill for Nwambi and Mambvumbvanyi (left) Hapi (centre) and Tlagelani (right). (outlined in Figure 4.32 but repeated here for ease of access).

The flood requirements that maintain PES conditions are given in **Table** 6.22. The data presented are the PES return period of pan filling, and the minimum discharges in the Luvuvhu River that breach the levees to flood the floodplain, or the combination of floods in the Luvuvhu and Limpopo Rivers together that backup to flood the floodplain and fill the pans.

Table 6.22: Flood requirements to maintain PES conditions of the Luvuvhu River floodplain and pans

Pan	Return period of pan filling	Source of flood	Minimum discharge (m3/s)
Nwambi and Mambvumbvanyi	1 : ~5 years*	Inflow (Luvuvhu River)	752
		Backfill (Luvuvhu and Limpopo River)	Refer to **Figure** 6-23 (top) for a combination of floods to maintain desired frequency
Hapi	1 : ~20 years*	Inflow (Luvuvhu River)	1 000 – 1 204
		N/A.	N/A.
Tlangelani	1 : 5 years*	Inflow (Luvuvhu River)	575
		Backfill (Luvuvhu and Limpopo River)	Refer to **Figure** 6-23 (bottom) for a combination of floods to maintain desired frequency

*In reality flooding/filling will be more frequent due to direct rainfall and associated runoff not considered in the values above

6.8.2 Lowflows in the Luvuvhu River

Perennial lowflows in the Luvuvhu River are important to sustain groundwater levels for the floodplain and riparian forests that rely on groundwater to persist through the dry season. The average depth to groundwater on the floodplain is shallow, ranging from 2.4 – 6.8 m (Ramsar Information Sheet 2007). Lite and Stromberg (2007) and Leenhouts *et al.* (2005) both showed that a reduction of 10% in lowflows reduced riparian forest density, and a reduction of 20% caused the trees to lose their competitive ability, so were replaced by hardy drought tolerant or terrestrial species. The maximum depth to groundwater in their study was 4 - 4.5 m.

Maintaining perennial lowflows in the Luvuvhu River is also critical to maintain pool depth as habitat for hippopotami, crocodiles and fish, especially in the 'hippo pool' at the confluence of the two rivers. This is especially important considering the Limpopo River only flows downstream of the Luvuvhu River in the dry season as a result of inflow from the Luvuvhu River.

6.8.3 Ecological Water Requirements at 18_Luvuvhu2

Ecological Water Requirements for lowflows, small floods (< 1:2 year return period) and larger floods (≥ 1:2 year return period). The larger floods are included in the EWRs because of their importance in maintaining the integrity and connectivity of the floodplain and pan ecosystem. Floods and lowflows must be maintained in the Luvuvhu River at 18_Luvuvhu2, at the upstream end of the Luvuvhu River floodplain. The EWRs are derived from:

- The PES flow scenario at 18_Luvuvhu2 for use prior to development. This will maintain the PES, a B/C category (**Table** 6.23)
- The Future1 flow scenario at 18_Luvuvhu2 for use after development. This will maintain a C category (**Table** 6.24).

Table 6.23: EWRs to maintain a B/C category at the Luvuvhu River floodplain

nMAR	684.802	MCM			
S.Dev.	59.346				
CV	0.087				
Q75	1.399				
Ecological Category	B/C				
	MCM	% nMAR			
Total EWR	325.505	47.533	Excludes floods with return period ≥1:2 years.		
Maint. Lowflows	257.382	37.585			
Drought Lowflows	164.938	24.085			
Maint. Highflows	68.123	9.948			
Monthly Distributions (MCM)					
	Natural	Modified Flows (EWR)			
		Lowflows		Highflows	Total EWR
Month	Mean	Maint.	Drought	Maint.	Maint.
Oct	16.618	4.515	6.044	0.789	5.304
Nov	26.380	7.941	7.790	3.134	11.076
Dec	51.665	15.830	11.889	15.911	26.298
Jan	106.801	35.912	20.703	47.738	51.233
Feb	173.508	58.163	27.922	91.650	72.761
Mar	138.716	63.627	31.124	51.285	78.426
Apr	64.796	36.422	20.073	8.115	44.217
May	32.384	13.348	11.265	0.865	14.214
Jun	23.561	7.965	8.568	0.109	8.074
Jul	19.651	5.897	7.401	0.099	5.996
Aug	16.205	4.176	6.378	0.017	4.193
Sep	14.517	3.585	5.781	0.129	3.714
Total	684.80	257.38	164.94	219.84	325.50

Floods. Flood can occur in the month before or after the month indicated								
	Within year floods <1:2 years				Inter annual floods >=1:2 years			
Flood Class	Class1	Class2	Class3	Class4	1:2	1:5	1:10	1:20
Ave peak discharge (m^3/s)	11.10	23.40	50.40	88.70	200	593	1029	1660
Ave duration (days)	4	6	8	10	10	15	20	34
Number	2	2	2	1	As per return period			
Oct								
Nov	1							
Dec	1	1						
Jan		1	1					
Feb				1	1	1	1	1
Mar			1					
Apr	1							
May								
Jun								
Jul								
Aug								
Sep								
Vol ($10^6 m^3$)	8.66	14.49	32.78	28.72	74.55	208.14	420.84	787.78
% PES (2022) MAR	1.81	3.04	6.87	6.02	15.62	43.61	88.19	165.08

Table 6.24: EWRs to maintain a C category at the Luvuvhu River floodplain

nMAR	684.802	MCM			
S.Dev.	59.346				
CV	0.087				
Q75	1.399				
Ecological Category	C				
	MCM	% nMAR	Excludes floods with return period ≥1:2 years.		
Total EWR	325.505	47.533			
Maint. Lowflows	257.382	37.585			
Drought Lowflows	164.938	24.085			
Maint. Highflows	68.123	9.948			
Monthly Distributions (MCM)					
	Natural	Modified Flows (EWR)			
		Lowflows		Highflows	Total EWR
Month	Mean	Maint.	Drought	Maint.	Maint.
Oct	16.618	4.515	6.044	0.789	5.304
Nov	26.380	7.941	7.790	3.134	11.076
Dec	51.665	15.830	11.889	15.911	26.298
Jan	106.801	35.912	20.703	47.738	51.233
Feb	173.508	58.163	27.922	91.650	72.761
Mar	138.716	63.627	31.124	51.285	78.426
Apr	64.796	36.422	20.073	8.115	44.217
May	32.384	13.348	11.265	0.865	14.214
Jun	23.561	7.965	8.568	0.109	8.074
Jul	19.651	5.897	7.401	0.099	5.996
Aug	16.205	4.176	6.378	0.017	4.193
Sep	14.517	3.585	5.781	0.129	3.714
Total	684.80	257.38	164.94	219.84	325.50

Floods. Flood can occur in the month before or after the month indicated								
	Within year floods <1:2 years				Inter annual floods >=1:2 years			
Flood Class	Class1	Class2	Class3	Class4	1:2	1:5	1:10	1:20
Ave peak discharge (m^3/s)	11.10	23.40	50.40	88.70	200	593	1029	1660
Ave duration (days)	5	7	9	9	10	15	20	34
Number	3	2	1	1	As per return period			
Oct								
Nov	1							
Dec		1						
Jan			1					
Feb				1	1	1	1	1
Mar	1	1						
Apr	1							
May								
Jun								
Jul								
Aug								
Sep								
Vol ($10^6 m^3$)	8.66	14.49	16.39	28.72	74.55	208.14	420.84	787.78
% PES (2022) MAR	1.81	3.04	3.43	6.02	15.62	43.61	88.19	165.08

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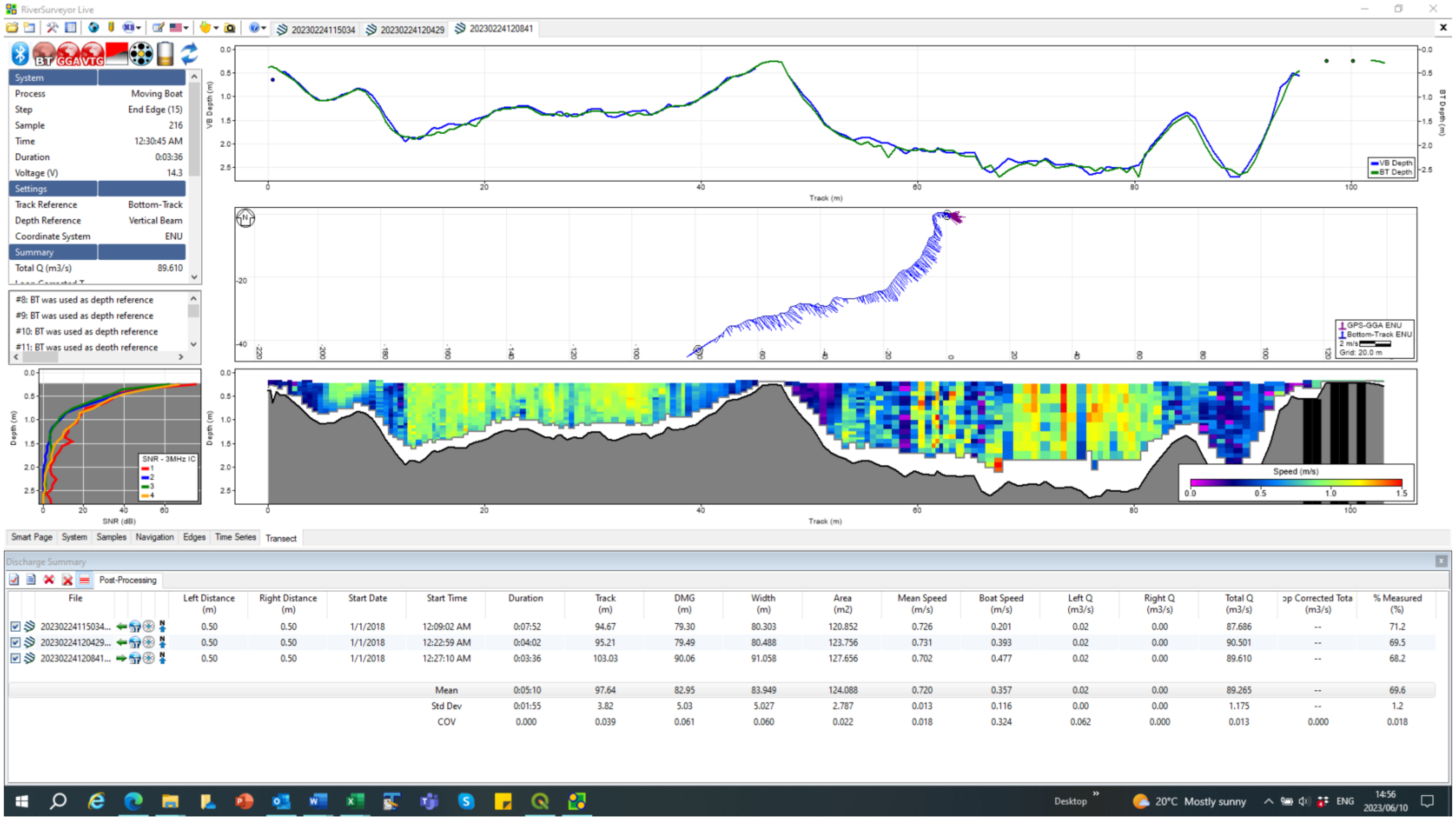
Appendix A. Acoustic doppler profile outputs



Appendix Figure 1: Sontek Acoustic Doppler Profiler discharge measurement along the Luvuvhu River at Pafuri Bridge on 24 February 2023 (89 m^3/s)