THE GOVERNMENT OF THE REPUBLIC OF MALAWI

MINISTRY OF AGRICULTURE IRRIGATION AND WATER DEVELOPMENT

SHIRE RIVER BASIN MANAGEMENT PROGRAMME (PHASE I) PROJECT

CLIMATE RESILIENT LIVELIHOODS AND SUSTAINABLE NATURAL RESOURCE MANAGEMENT IN THE ELEPHANT MARSH, MALAWI

Sub-Study 2:
Hydromorphology of the Elephant Marsh

Prepared by:

Streamflow Solutions

Southern Waters

In Association with:

MRAG

December 2016

"No important work is ever accomplished without considerable trouble"

David Livingstone, Elephant Marsh, 1863

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Streamflow Solutions cc Streamflow Solutions is based in East London (SA). Its focus since inception in 1998 has been the development and application of eco-hydraulics for the assessment of Environmental Flows in rivers, floodplains and wetlands, and for the assessment of impacts resulting from water resource developments. The interdisciplinary nature of this field has meant extensive interactions with hydrologists, fluvial geomorphologists, ecologists and social scientists. Specifically, Streamflow Solutions carries out topographical and bathymetric surveys, the design and installation of hydraulic data-collection systems, digital elevation and hydrodynamic (one and two-dimensional) modelling, software development, and habitat mapping using remote sensing.
Southern Waters Ecological Research and Consulting cc Southern Waters provides a service to public and private organisations in advising on the sustainable management of inland and coastal aquatic systems. Its members contribute to the body of fundamental knowledge on the structure and functioning of these ecosystems, and it has retained a research and teaching component through its direct links with an academic institution. Southern Waters focuses on freshwater ecosystems and, as such, has a wealth of knowledge on the nature, condition, functioning and management of rivers and other inland waters, both in southern Africa and abroad.

Report history

Version	Scope	Date
1	Prepared by Andrew Birkhead (Streamflow Solutions) and Karl Reinecke (Southern Waters)	21/11/2016
2	Reviewed by Cate Brown (Southern Waters)	24/11/2016
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Acknowledgements

The Elephant Marsh had rather a reputation for boats getting stuck in the 19th century:
"In ascending this river with the Lady Nyasa in tow alongside, we had no difficulty till we got to the Elephant Marsh, and there in sudden bends we found it an awkward matter to get along, for two vessels cannot be turned so quickly as one, and Lady Nyasa being pretty deep would go aground, and was very difficult to get off ... so we have lost more time than we anticipated" (Livingstone, 1863)

"*He [Thornton] overtook the steamers [Livingstone's Pioneer and Lady Nyasa] on the 28th of January near the 'Elephant Marsh' on the Shire, and accompanied them in their slow progress amongst the shoals of that much-obstructed river...*" (Thornton, 1864)

"*On Monday last we steamed on to the middle of the Elephant Swamp and there stuck. There was no passage of 4 ft to take us through. We have had a week's hauling in the meantime ... still in the middle of the Elephant Swamp*" Kirk (1865)

"...so after all, if the boat did sink, it would not be quite up with us. All we had now to guard against was sticking on sand-banks. This was not very easy, because the river was getting full of shallows, and in some places the men had to get out and wade before they could push the boat along. Every now and then we came to a dead halt; and as we got off again, we heard the boat grating along the bottom of the river." Pringle (1886)

Technology has advanced from that era of paddle steamers with coal-fired boilers, to the extreme horsepower airboats of today, but some things don't change. And so it was in September 2015, some 25 km into the thick of the Marsh that our high-tech mode of transport failed. There certainly is no better way to experience the Elephant Marsh's reed-lined web of channels, the vast expanses of its beautiful lakes, hippos with attitude, and mosquito population, than a 15-hour pole into the sunset and darkness of the ensuing hours. Our sincere thanks to the many fisherman we encountered along the way that assisted us on that slower journey back to base. What was "*lost in time*", was more than gained in adventure.

Elephant Marsh, September 2015

Local fisherman aside, many people and organisations contributed to the success of this study, for which they are gratefully acknowledged:

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Prof Marion Bamford and Dr Jennifer Fitchett (Evolutionary Studies Institute, University of the Witwatersrand, Johannesburg, SA);

Dr Palamuleni (North West University, SA);

satellite imagery and mapped flood extents from various sources: USGS EarthExplorer, Centre for Satellite based Crises Information of the German Aerospace Centre, SA Space Agency, and Blackbridge, and;

the highly-valued and utilised public-domain GIS software: SAGA GIS and Quantum GIS.

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Acronyms and abbreviations

AD	Anno Domini
ALC	African Lakes Company
ALOS	Advanced Land Observing Satellite
AMS	Accelerometer Mass Spectrometry
amsl	above mean sea level
an	annum
AOI	Area of Interest
API	Antecedent Precipitation Index
AW3D30	ALOS World 3-d 30 (metre)
BCAC	British Central African Company
BP	Before Present
CFGEN	ConFig GENerator
CRS	Coordinate Reference System
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
DoS	Department of Surveys (Malawi)
DRIFT	Downstream Response to Imposed Flow Transformation
e.g.	for example
ENSO	El Niño Southern Oscillation
ft	feet
GE	Google Earth
GCM	Global Circulation Model
GIS	geographical Information System
GPS	Global Positioning System
ha	hectare
HPP	HydroPower Project
i.e.	that it
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
IPCC	Intergovernmental Panel on Climate Change
JIKA	Japan International Cooperation Agency
ka	kilo annum (1000 years)
LULUCF	LandUse, LandUse Change and Forestry
LiDAR	Light Detection and Ranging
m/s	metres per second
m/yr	metres per year
m3/s	cubic metres per second
Ma	Mega annum (million years)
MAR	Mean Annual Runoff
MASDAP	Malawi Spatial Data Portal
mm/yr	mm per year
msl	mean sea level
MoIWD	Ministry of Irrigation and Water Development, Malawi
NDVI	Normalised Difference Vegetation Index
NIR	Near InfraRed
NWRMP	National Water Resources Master Plan

pa	per annum
pMC	percent Modern Carbon
RE	Rapid Eye
RMAGEN	RMA geometry GENerator
RMA2	Resource Modelling Associates 2-d
RMAPLT	RMA PLoT
RUSLE	Revised Universal Soil Loss Equation
SA	South Africa
SHR	Shire Highlands Company
SRBMP	Shire River Basin Management Programme
SRTM	Shuttle Radar Topography Mission
SVP	Shire Valley Project
SWAT	Soil Water Assessment Tool
t/ha/an	tons per hectare per annum
TA	Traditional Authority
TIFF	Tagged Image File Format
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
USACE	United States Army Corps of Engineers
viz.	namely
WES	Waterways Experiment Station
WGS84	World Geodetic System 1984
WRIS	Water Resources Investment Strategy
WRU	Water Resource Unit
ZKI/DLR	Centre for Satellite based Crises Information (ZKI) of the German Aerospace Centre (DLR)
1-d	one-dimensional
2-d	two-dimensional
~	approximate

Terminology

barrage	Kamuzu Barrage at Liwonde
floating-leaved	aquatic vegetation with floating leaves
lake	refers to either Lake Malawi or the shallow lakes in the Elephant Marsh - which of these is being referred to is evident in the context
Lake Bangula	large marsh lake adjacent to Kaombe Sugar Estate with two arms (north-eastern and south-western); not to be confused with the lake due east of Bangula Village and south of the railway embankment
Marsh	Elephant Marsh

1 Introduction and background

The Government of Malawi received a credit and a grant from the International Development Agency (World Bank Group) to finance the implementation of the Shire River Basin Management Programme (SRBMP) Phase I Project. The overall programme development objective of the SRBMP is to increase sustainable social, economic and environmental benefits by effectively and collaboratively developing and managing the Shire River Basin's natural resources.

This project, entitled 'Climate resilient livelihoods and sustainable natural resources management in the Elephant Marsh, Malawi', contributes to the above aim by generating an understanding of the functional ecology of the Elephant Marsh, incorporating studies of the hydromorphology, ecosystem services, biodiversity and livelihoods; and modelling of past, present, and future possible management strategies. The assignment also assesses the feasibility of designating the Marsh as a community-managed protected area and as a wetland of international importance under the Ramsar convention.[1]

This report covers the hydromorphology component of the Elephant Marsh Project (P117617).

At the outset, it is worthwhile defining what is meant by 'hydromorphology'. Vogel (2011) describes several conflicting definitions, and notes that none of them were in widespread use five years ago. Hydromorphology was defined by Newson and Large (2006) and similarly by Orr (2008), as the physical habitat constituted by the flow regime (hydrology and hydraulics) and the physical template (fluvial geomorphology). In the absence of an explicit definition, Vogel contends that its implied meaning may also incorporate a blend of ecology. The description offered by Vogel is broad, this being that it is a subfield of hydrology (engineering and science) that deals with problems relating to the structure, evolution, and dynamic morphology of hydrological systems over time (e.g., years to centuries). He explains that this definition arises from the growing need for society to deal more directly with the profound environmental and water-resource impacts that are being generated by human activities. Vogel's definition is most appropriate for this study, since it incorporates aspects of hydrology, hydraulics, fluvial morphology and ecology, considered over a time frame of more than a century, within social and environmental contexts.

1.1 Objectives of this sub-study

The hydromorphology sub-study has the following objectives:

- establish the current status and recent trends in the hydromorphology of the marsh;
- develop a hydraulic model for predicting flooding patterns in the Marsh, retrospectively, based on the entire flow record;[2]
- evaluate historic landuse change (especially deforestation and agriculture) and its effect on sedimentation and siltation of the Marsh;
- map historic changes in the channel patterns of the Marsh.

[1] If considered feasible, then the intention is to generate the information required to support an application for designation of the Elephant Marsh as a Ramsar site, and develop an integrated management plan for the Marsh that supports community-based management.

[2] The 'entire' record for the Marsh is limited by the length of record from the hydrometric station at Chikwawa, which is 33 years (1976 to 2009) - refer to Chapter 3, 'Hydrology of the Marsh'.

1.2 Layout of the report

The objectives of the sub-study have been met through extensive literature reviews; collation, review and analyses of existing data; field-based data collection and analyses; and hydrological and hydraulic modelling. The results of these endeavours are presented in seven chapters, as follows:

1. Introduction and background (this chapter)
2. Historical accounts and records: Shire River, Elephant Marsh and Lake Malawi
3. Hydrology of the Marsh
4. Channel change, flooding and landuse/vegetation distributions in the Marsh
5. Hydrodynamic modelling of the Marsh
6. Upstream catchment landuse and Marsh sedimentation
7. Hydromorphological functioning of the Marsh: contextualisation, past behaviour and future resilience

Chapter 2 provides a record of historical accounts of the Shire River, Elephant Marsh and Lake Malawi. These include the first recorded descriptions of the Shire River and Elephant Marsh from Livingstone's Zambezi Expedition in the mid-1800s; other accounts from travellers moving through the Marsh; the development of river and railway transport in the region; and information from the Shire Valley Project (SVP), which was initiated in the 1940s. A discussion of historical water-level fluctuations in Lake Malawi is also provided, relevant insofar as Lake Malawi is the source of flow to the Shire River, and that lake levels are a sensitive indicator of regional climate change.

The next three chapters (3, 4 and 5) contribute towards the development of a hydrodynamic model for predicting flooding patterns in the Marsh in the period since flow records began. In Chapter 3, the hydrology of the Marsh is discussed, and this section includes data collation and review; analyses and modelling of discharge time-series, and a sub-section on climate change. Chapter 4 deals with descriptions and mapping of historic channel change, flooding extent, and landuse and vegetation distributions in the Marsh. This mapping is fundamental to the development of the hydrodynamic model, presented in Chapter 5, which also includes a background and review of existing models; discussion of the approach adopted in this study; data; and model development, calibration and application using different (hydrological) scenarios.

The penultimate chapter (6) describes upstream catchment landuse based on available literature, and the sedimentation of the Marsh. The latter includes a description of data collection in the form of sediment cores, suspended sediments, and water chemistry. Results of radiocarbon dating of samples from cores extracted at different locations along the Marsh, and suspended sediment sampling over the course of a year are discussed.

The final chapter (7) commences by contextualising the Elephant Marsh based on a review of large southern African wetlands. It then presents a synthesis of preceding sections, detailing past trends in the hydromorphological functioning of the Marsh, providing an assessment of its perceived resilience.

1.3 Geographical, hydropower and hydrological context

The Elephant Marsh,[3] one of Malawi's first wildlife protection areas (Jawali, 2015), lies on the floodplain of the lower Shire (or Tchiri) River between the towns of Chikwawa and Chiromo in southern Malawi (Figure 1.1 and Figure 1.2). The Marsh was named by David Livingstone in 1859,[4] who counted hundreds of elephants in one sighting. Today, the elephants are gone, but the Marsh supports numerous aquatic birds, fisheries, crocodiles, and a few remnant hippopotami. Because the Marsh is difficult to define, its area is variously quoted between 400 and 1 200 km^2. The uncertainty is because it varies considerably in size between seasons and years.[5]

In the north-west, it is typically a seasonal wetland; centrally, it is semi-permanent marshland, and; in the south, it is characterised by semi-permanent marsh and shallow lakes.[6] The Marsh supports floating mats of vegetation (termed 'sudd') and its margins are lined with palm and fever trees. The Ruo River, the largest tributary of the Shire River, and the southeast boundary with Mozambique, joins the Shire near the village of Chiromo.[7]

The immediate Area of Interest (AOI) for this study extended from Chikwawa Bridge (upstream) to Chiromo Bridge (downstream) (Figure 1.2), largely determined by the location of hydrometric stations. To understand the Marsh's hydromorphology and develop a hydrodynamic model, it was necessary to consider the hydrology of the upstream Shire River Basin, including its source, Lake Malawi. It was also necessary to include sub-catchments adjacent to the AOI, and the Ruo River.

The Lake Malawi-Shire River hydrological system represents Malawi's single most important natural resource, providing water for various anthropogenic uses, including: hydropower; agriculture; fisheries; transport; tourism, and; urban and rural users (World Bank, 2012). The river flows for 520 km through the southern region of Malawi and is joined by numerous tributaries along its length before discharging into the Zambezi River near the town of Caia in Mozambique. The upper Shire is at an elevation of ~474 m above mean sea level (amsl) (Figure 1.3).

Downstream of Lake Malawi, between Lake Malombe and the Kamuzu Barrage at Liwonde (Figure 1.4) the river flows at a gentle gradient. The barrage was constructed in 1965[8] to partially control both the upstream water-level, which backs-up through Lake Malombe to Lake Malawi,[9] and the downstream discharge of the Shire River to support hydropower.

From Liwonde, the Shire falls only seven metres over 50 km, but thereafter drops a further 360 m over ~70 km through a series of rapids and falls where three hydropower plants (HPPs), developed between 1966 and 2014, are located: Nkula (Figure 1.5), Tedzani, and Kapichira (Figure 1.6). The total installed capacity is 346.3 MW[10] and accounts for 98% of Malawi's grid-based electricity. The three HPPs are often referred to as 'run-of-river',[11] since their reservoir storage capacities are limited. Their capacities

[3] also known as the 'Dabanyi Marsh' (Mandala, 1984, as cited by Jawali, 2015)
[4] refer to Chapter 2, 'Historical accounts and records: Shire River, Elephant Marsh and Lake Malawi'
[5] http://www.malawitourism.com
[6] refers to recent (decadal) characteristics
[7] The Ruo River changed its recent historical (at least 150-year) low-flow course during the extreme floods of January 2015, and now flows directly into the Marsh. This is discussed in various sections of this report.
[8] After more than 50 years of operation, the Kamuzu Barrage is currently being upgraded with funds allocated from Phase 1 of the SRBMP.
[9] effectively, the available or live storage for downstream use
[10] http://www.escom.mw/generation.php (accessed 18 August 2016)
[11] Although this description is at odds with a recent World Bank Group definition of run-of-river, which is: hydropower plants that release downstream into the same river, with a short or no diversion, have ≤ 48-hour dry-season storage and do not make peaking-power releases (World Bank Group, 2016).

have reduced further due to sedimentation: the Nkula and Kapichira Reservoir's had only 30% of their live storage in 1996 and 2003, respectively (Kaunda and Mtalo, 2013).[12] Since storage is limited, power generation largely depends on flows from upstream. Daily water-level fluctuations are evident in the observed hydrometric record at Chikwawa,[13] but not at Chiromo, as by then they have been attenuated by the Marsh's hydrodynamics.

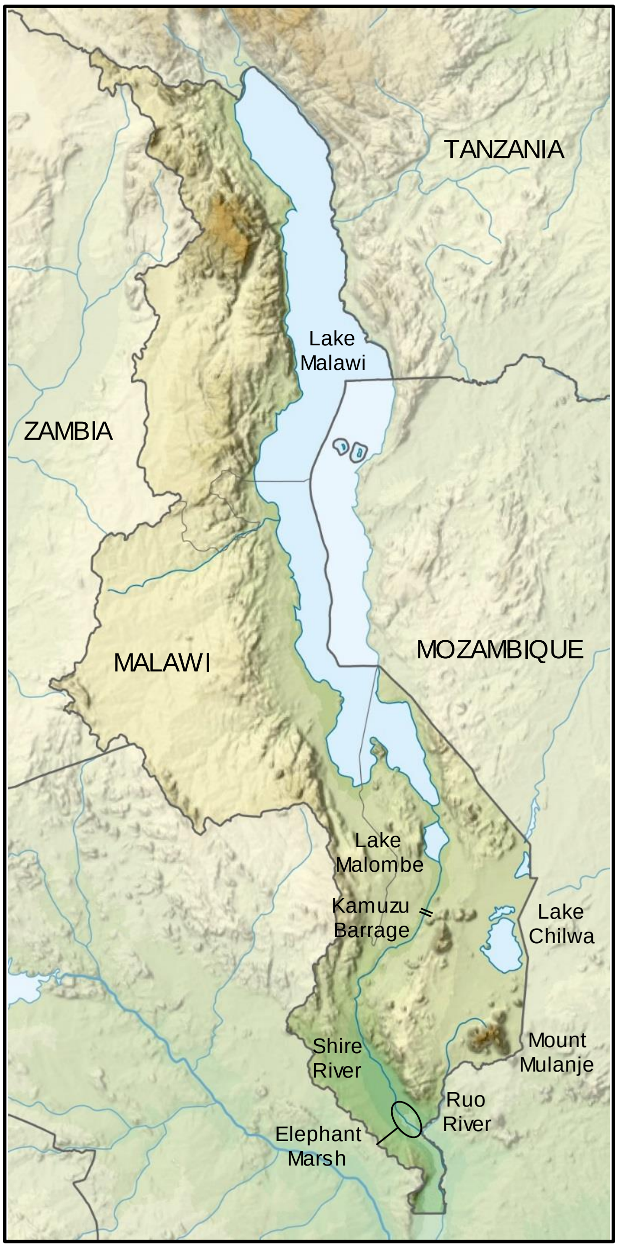

Figure 1.1 Location of the Elephant Marsh on the lower Shire River in southern Malawi

[12] Dredging operations have been carried out to recover storage capacities - refer to Figure 6.5.
[13] up to half a metre or so

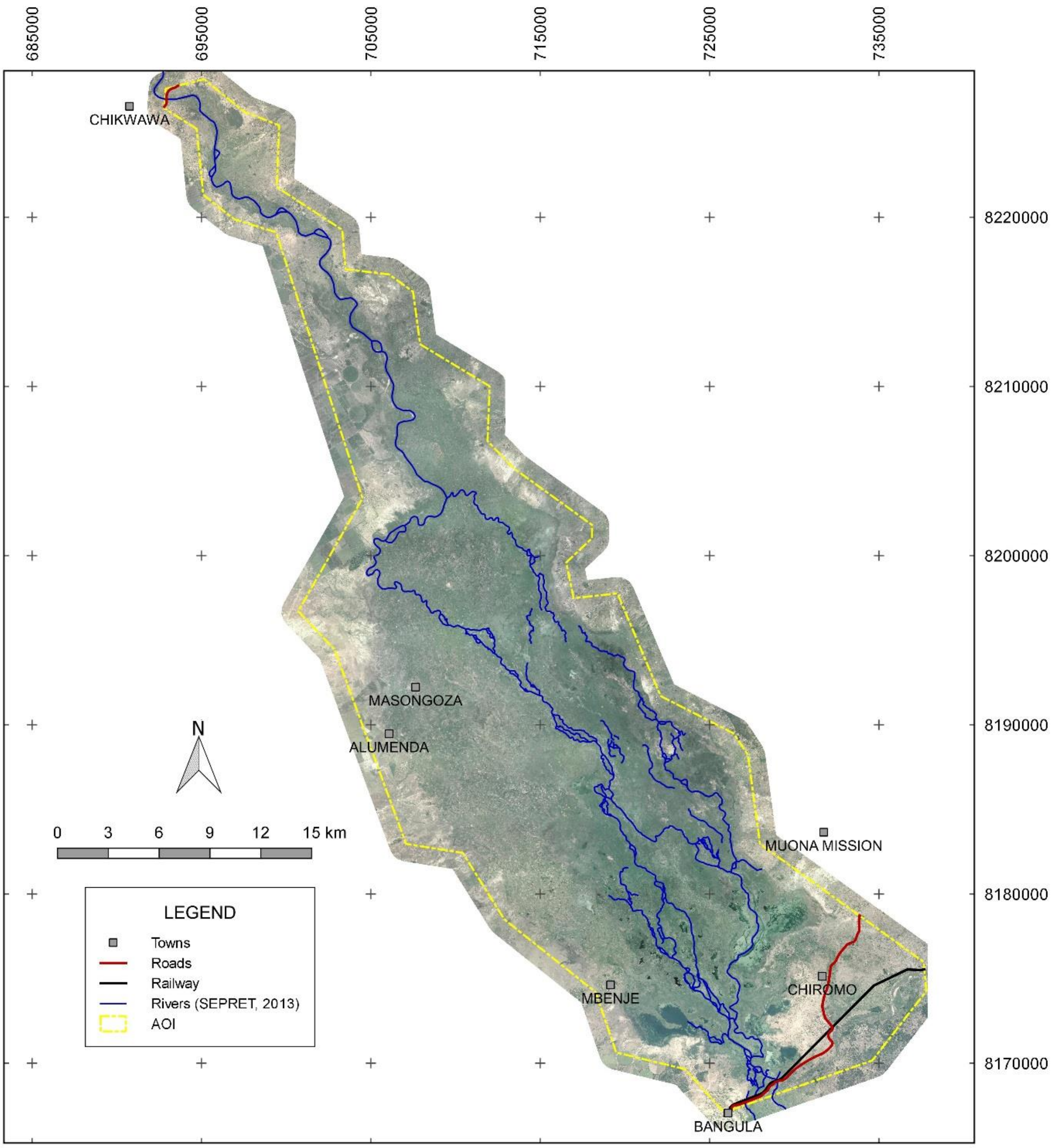

Figure 1.2 **Location of the Area of Interest (AOI) for this study between the Chikwawa and Chiromo Bridges; the background orthophotograph is circa 2013 (SEPRET, 2014); CRS is Arc 1950 (Malawi)**

The Lower Shire emerges from the Kapichira Falls and enters a floodplain system with a progressively decreasing longitudinal gradient to the river's confluence with the Zambezi, ~320 km further downstream (at an elevation of ~30 m amsl). The wetlands associated with these floodplains are considered to play an important role in reducing downstream sediment and flooding. The lower Shire Floodplain system hosts large areas of traditional and commercial[14] agriculture, and more than half a million people live in areas adjacent to the river that are susceptible to flooding, and includes the

[14] mainly sugar cane

Elephant Marsh, which supports extensive cultivation, high biodiversity and a productive fishery (World Bank, 2012).

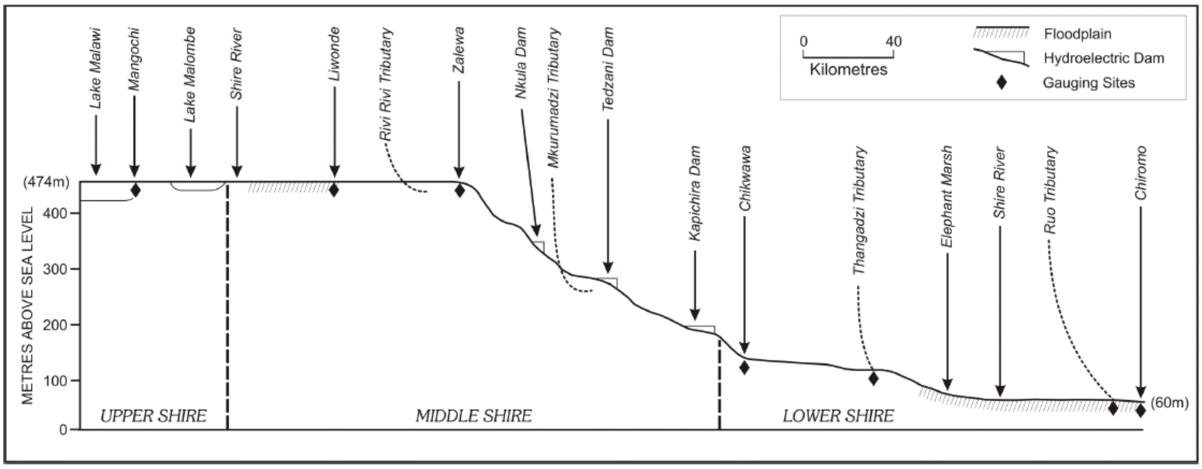

Figure 1.3 **Upper, middle and lower reaches of the Shire River between Lake Malawi and Chiromo, showing the positions of tributaries,[15] hydropower projects (HPPs), hydrometric stations and the Elephant Marsh along the floodplain (after Chimatiro, 2004)**

Figure 1.4 **The Kamuzu Barrage at Liwonde constructed in 1965 to regulate upstream water levels in Lake Malawi and downstream discharges in the Shire River for hydropower**

[15] The Thangadzi River tributary upstream of the Elephant Marsh is incorrect, it is likely the Mwanza River

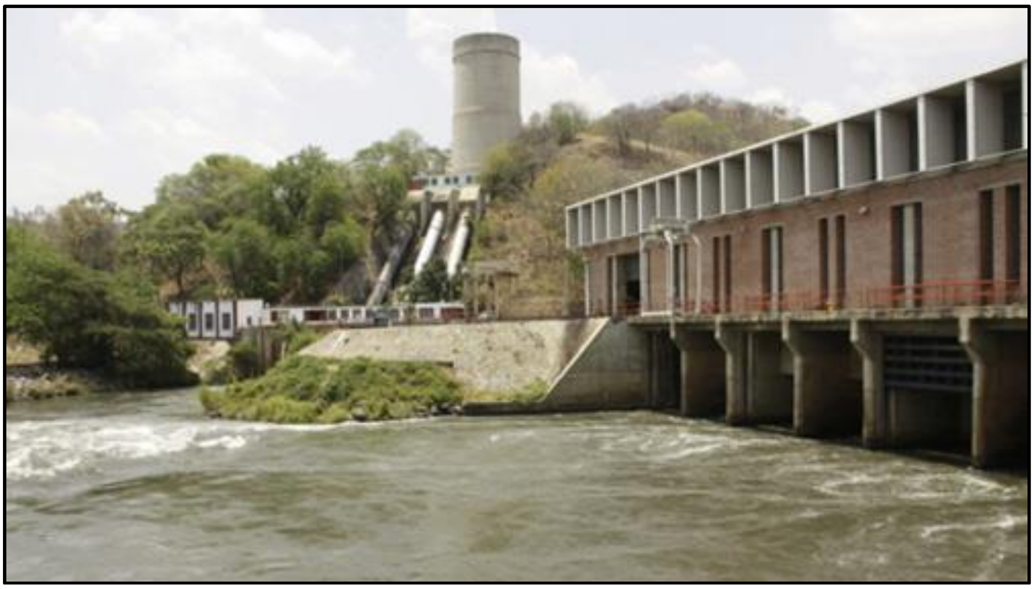

Figure 1.5 The Nkula HPP, which has an installed capacity of 124 MW

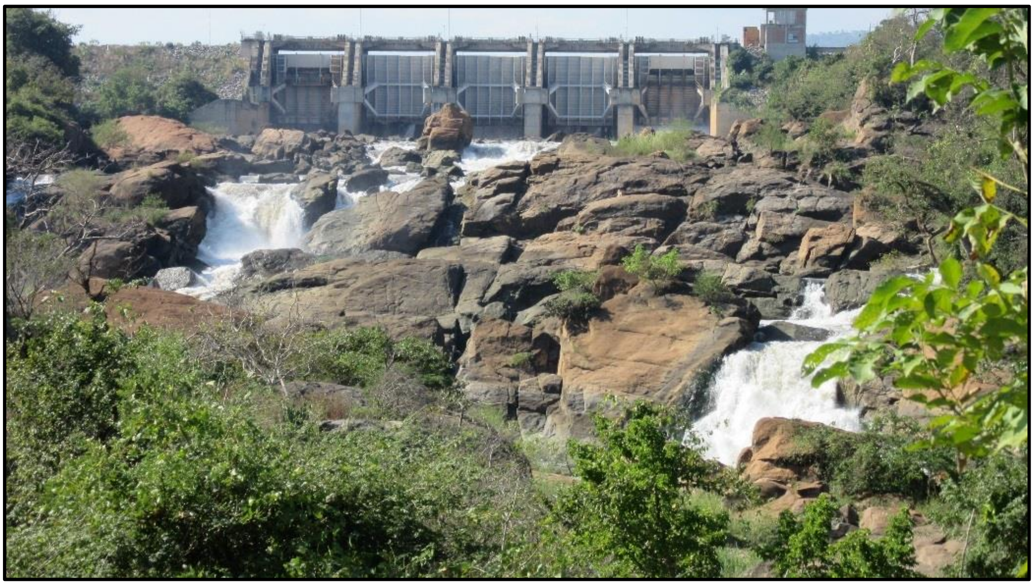

Figure 1.6 Kapichira Falls and its associated HPP, the capacity of which was doubled in 2014 to 130 MW is the largest of the three Shire River HPPs

Lake Malawi is, together with Tanganyika and Baikal[16], one of the few deep-water long-lived lakes that exist on earth (Delvaux, 1995). It is a dynamic system, enclosed in the active East African Rift that comprises two branches: the Eastern (or Kenya) and Western Rift Valleys (Figure 1.7). The Western Rift runs from Lake Albert to the Indian Ocean through the Tanganyika and Malawi Rift Valleys. The Lake is ~550 km long and ~50 km wide, with mean and maximum depths of 273 and 706 m, respectively. The lake volume is 6 140 km^3, and its surface area is about one-third its drainage-basin area (22 490 and 65 000[17] km^2, respectively).

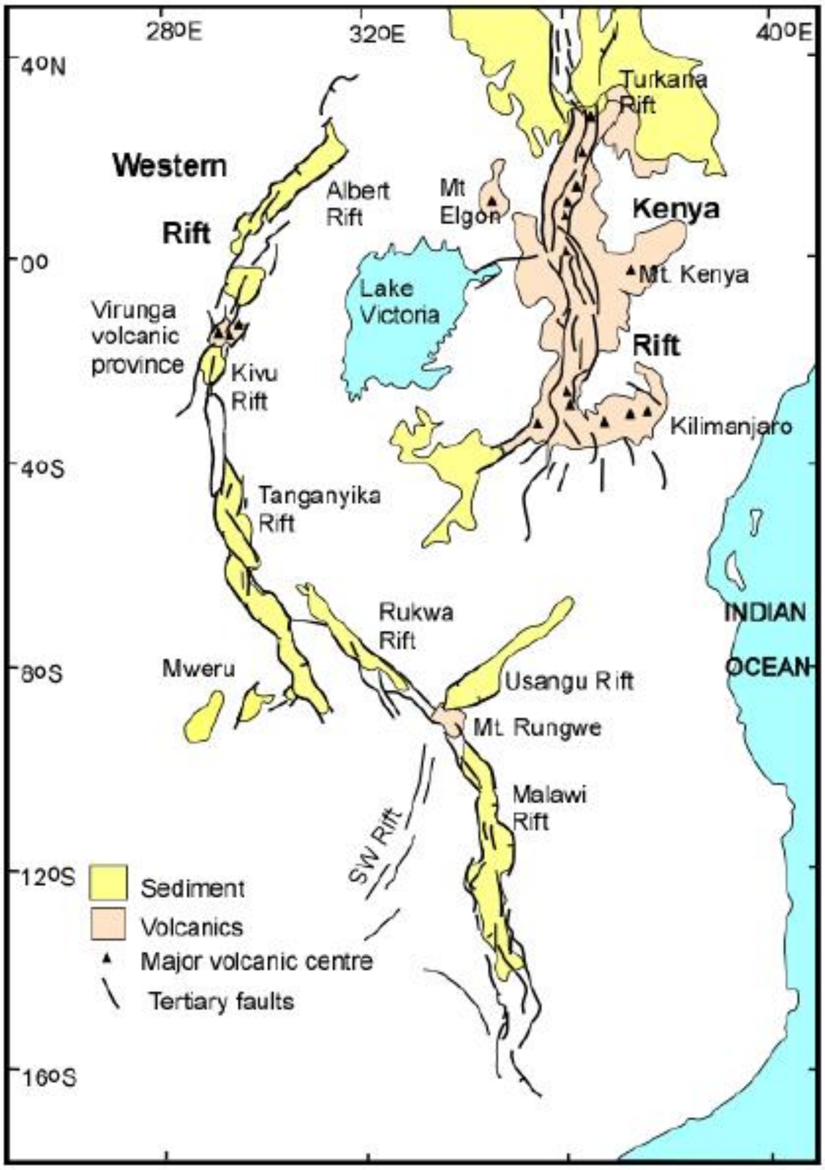

Figure 1.7 **The structural relationships between the Eastern (Kenya) and Western branches of the East African Rift system (after Omenda, 2009)**

[16] in Siberia
[17] Johnston and Ng'ang'a (1990)

The outflow from Lake Malawi, which constitutes the source of the Shire River, is determined by lake level, which has been partially[18] regulated over the past half-century by operation of the Kamuzu Barrage at Liwonde. Lake levels have been recorded since the late 19th century[19] (Figure 1.8) and can be used to infer[20] (unregulated) Shire River flows, even though flow measurements at Liwonde only commenced in 1948. Recorded lake levels over the past 120 years ae also invaluable for assessing the effects of climate change (on the hydrological water balance and Shire River flows), and have been used in many studies for this purpose (e.g., Drayton, 1984; Delvaux, 1995; Nicholson, 1998).

Prior to the earliest studies of lake hydrology by Kanthack (1942), Cochrane (1957) and Pike (1968a, 1968b) there were various speculations[21] on the causes of long-term changes in lake levels. Kanthack (1942) elucidated (later confirmed by Cochrane, 1957) the subtle balance between rainfall, runoff, evaporation and outflow, and attributed level changes simply to the lake's hydrological water balance. According to Johnson and Ng'ang'a (1990), outflow comprises only one-fifth of total water loss, and the bulk of the water is lost to evaporation.

Expressed in terms of average changes in lake level:

- rainfall and runoff add 1.73 to 2.50 m/yr (metres/year);
- evaporation averages ~1.90 m/yr, and;
- Shire River outflow is ~0.45 m/yr (Pike, 1968a).

The large relative evaporation losses result in lake levels (and therefore outflows) that are sensitive to the balance between rainfall and evaporation, and hence, climate change. This has been highlighted in numerous studies (e.g., Drayton, 1984; Delvaux, 1995; Shela, 2000; Jury and Gwazantini, 2002; Kaunda and Mtalo, 2013), and is graphically illustrated in Figure 1.9, which includes plots of historical and unregulated[22] Shire River outflows. Outflows over the last 120 to 150[23] years from the complete cessation of flow (during the early part of the 20th century - refer to Chapter 2) to a maximum annual average of ~850 m^3/s during the 1979/80 hydrological year.

Appreciation of the long-term changes in lake levels, Shire River flows and underlying climate change is fundamental to developing an understanding of historical changes in the Marsh. This, in turn, provides a sound basis for assessing its capacity for resilience in the future. In the next chapter, historical accounts and records spanning the past century and a half are presented.

[18] When lake levels are high, essentially natural flows are released at Kamuzu Barrage

[19] Although this is widely stated in the literature, Maxwell (1954) points out that the levels between 1915 to 1920 were uncertain, as Commander Rhoades, the ship's Officer, that carried out observations of annual rise and fall (as a "*spare time hobby*"), was away from Nyasaland for this period. Rhoades did what he could to patch the missing data, but *"... he became certain that the levels supplied were not correct* ...". Maxwell's description of events is not entirely clear, but implies that the stage datum was lost, which was difficult to re-instate with a rising lake level. He advised that the situation be remedied - the extent to which this was done, is unknown.

[20] and ratify (or otherwise) accounts of historical flow behaviour in the lower Shire River

[21] as described by Arnold (1952), "... *to the borders on the occult* ..."

[22] or capacity rating curve (Norplan, 2013)

[23] inferred from probable levels between 1860 and 1896, plotted in Figure 1.8

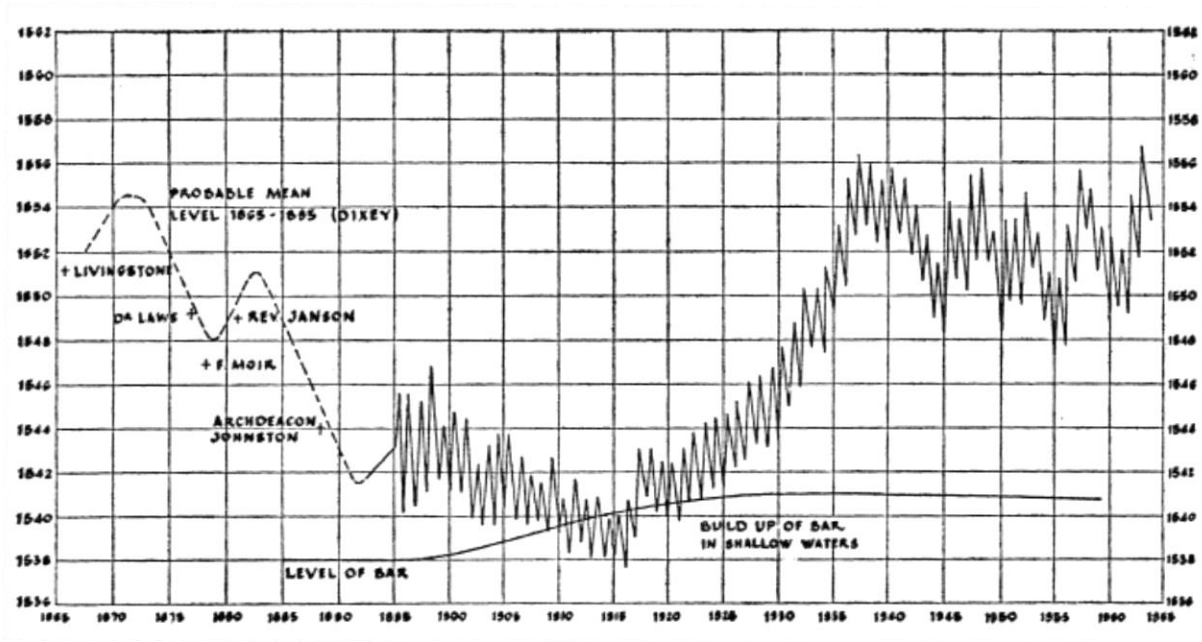

Figure 1.8 **Observed level[24] of Lake Malawi 1895 to 1963, with probable levels between 1860 and 1896 compiled from various historical sources by Latham, 1960 (after Pike, 1968a)**

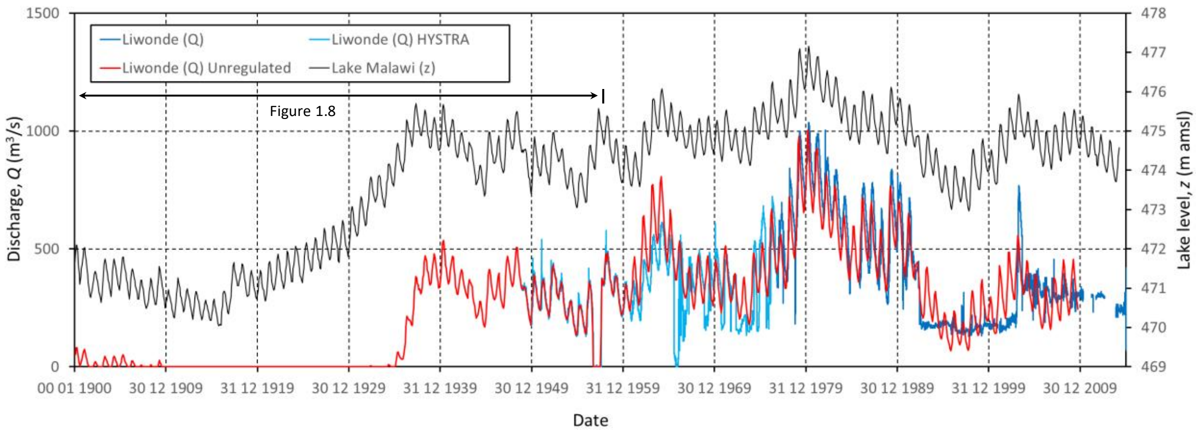

Figure 1.9 **Level of Lake Malawi (1900 to 2014) and measurement-based discharge[25] at Liwonde (Station 1B1 - refer to Section 3.2.1) (1948 to 2009), indicating the relative plotting position of the graph in Figure 1.8; also plotted is the unregulated[26] (naturalised) discharge at Liwonde**

[24] in feet
[25] The discharge pre-01/11/1976 (HYDSTRA) was obtained from the MoIWD; for post-01/11/1976 the time-series has been recalculated using rating relationships refined within this study (refer to Section 3.4.1) (both are daily time-series)
[26] or capacity rating curve (Norplan, 2013)

2 Historical accounts and records: Shire River, Elephant Marsh and Lake Malawi

2.1 Descriptions of the Marsh from Livingstone's Zambezi expedition 1858 to 1864

The explorers of the mid-to-late 1880s and their comprehensive records in the form of travel descriptions and maps provide valuable insights to the early character of the Shire River in general and the Elephant Marsh in particular. The study of the Marsh's morphological change greatly benefits from such an historical record and a concerted effort has been made to collate and digest the earliest known descriptions of the Marsh.

As mentioned previously, the Elephant Marsh was named for the large herds of elephant observed by David Livingstone during his 1859 trips along the Shire River. His descriptions and those of his travelling companions,[27] in the form of accounts, photographs and sketches offer invaluable insights into nature of the Marsh 150 years ago.

Livingstone returned to Africa in 1858 on the Zambezi Expedition, not as a missionary, but as H.M. Consul at Quilimane[28] for the East Coast of Africa to the south of the dominions of Zanzibar and for the independent districts of the interior, and Commander of an expedition to explore eastern and central Africa. A river paddle-steamer of light draught, the *Ma-Robert* (Figure 2.1), was procured for the Zambezi Expedition. Livingston's party included, *inter alia*, Commander Bedingfield, John Kirk (naturalist and physician), Baines (artist), and Richard Thornton (geologist and surveyor). Early on Bedingfield resigned from the expedition and Livingston took charge of the *Ma-Robert*. Travelling up the Zambezi River, he found his way barred by the impassable Cahora Bassa Rapids.[29] The *Ma-Robert* turned out a failure for upstream travel on the Zambezi, and a more suitable vessel was sought. Meanwhile, however, Livingstone remained determined to find a river route into the interior and decided to use the *Ma-Robert* to explore the Shire River and the great lake reputed to be at its source.

The first trip up the Shire River was made early in 1859 but, after two hundred miles of navigation with the *Ma-Robert*,[30] Livingstone and Kirk were stopped by impassable rapids and cataracts, which were named Murchison (re-named Kapichira), and by local 'hostilities', and were forced to retreat. They returned in March of the same year, leaving the steamer at Katunga. There has been uncertainty regarding the location of Katunga (refer to Bamford, 2009; Welling; 2009), but Johnston's 1898 hand-drawn and detailed map of the Shire River between Chiromo and Chikwawa (e.g., Figure 4.5) indicates the river station (known as Katunga) of the African Lakes Company (ALC) between the left (eastern) bank of the Shire River and northern bank of the Mwamphanzi River Delta[31] (refer to Figure 4.6). In modern terms, this is ~4.2 km downstream[32] of the Kamuzu Bridge at Chikwawa. In August of 1959 Livingstone made a third trip up the Shire, proceeding overland from Katunga, and 'discovering' the source of the Shire River, Lake Malawi - his party being the first white Europeans to gaze across its waters.

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[27] including Livingstone's letters written during the Zambezi Expedition; Thornton (1864); Kirk (1865); Livingstone and Livingstone (1893); Gelfand (1974); Ditsas (2010); Milbrandt (2014); and on-line reference: http://www.wholesomewords.org/missions/bliving3.html (accessed 31/08/2016)

[28] Mozambican town

[29] also referred to as the Kebrabasa Rapids, which he visited three times to ensure they were an insuperable barrier to continuous navigation of the Zambezi River

[30] the vessel had a draft of 3 feet (~1 m)

[31] Interestingly, "New Katunga" is indicated downstream of a marsh formed by the Mwamphanzi River Delta but this has been crossed-out and re-named "Mission Station".

[32] straight-line distance

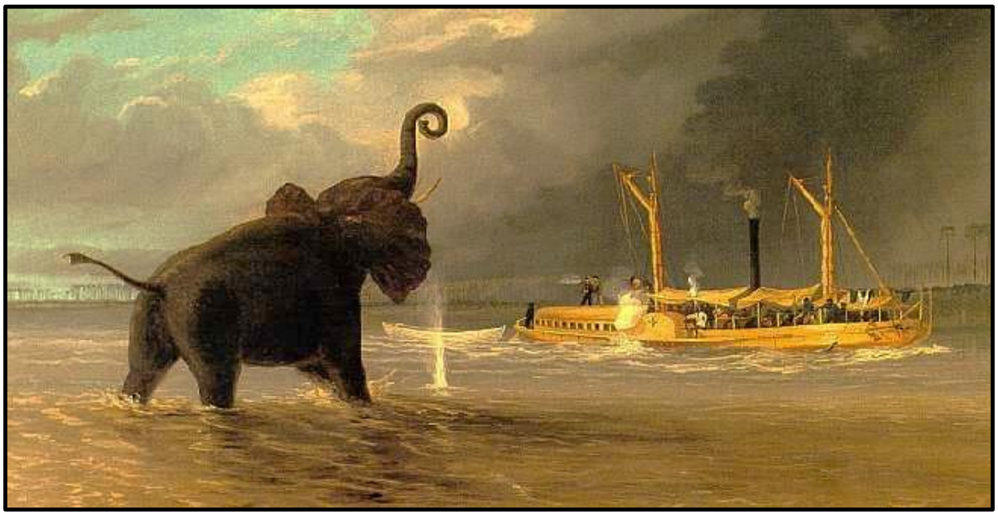

Figure 2.1 **"*Elephant in the Shallows of the Shire River, the Stream Launch [*the *Ma Robert] Firing*", 1959 painting by Thomas Baines (1820 - 1875)**

The following excerpts from "*Narrative of an expedition to the Zambesi and its tributaries: and of the discovery of the Lakes Shirwa and Nyasa, 1858-1864*" (Livingstone and Livingstone, 1893) are the Livingstone brothers' descriptions of the Elephant Marsh from their August 1859 expedition. Reference is made to the original local name for the Marsh and its impenetrable character:
"*A short way beyond the Ruo lies the Elephant Marsh, or Nyanza Mukulu,*[33] *which is frequented by vast herds of these animals. We believe that we counted eight hundred elephants in sight at once. In the choice of such a strong-hold they have shown their usual sagacity, for no hunter can get near them through the swamps. They now keep far from the steamer; but when she first came up, we steamed into the midst of a herd, and some were shot from the ship's deck. A single lesson was sufficient to teach them that the puffing monster was a thing to be avoided; and at the first glimpse they are now off two or three miles to the midst of the marsh, which is furrowed in every direction by wandering branches of the Shire. A fine young elephant was here caught alive, as he was climbing up the bank to follow his retreating dam*."

Descriptions are provided of aquatic marsh habitat, including *"small lagoons; almost stagnant channels*" that supported "*prodigious numbers of many kinds of water-fowl*". Others refer to gathering and fishing activities: "*Groups of men and boys are searching diligently in various places for lotus and other roota. Some are standing in canoes, on the weed-covered ponds, spearing fish, while others are punting over the small intersecting streams to examine their sunken fish-baskets*." It seems, however, that these references are to the Shire marshes in general, and the existence of "*lagoons*" or "*ponds*" in the Elephant Marsh *circa* 1959 is unknown.

The following description of extensive palm trees is markedly different from the existing morphology, and is supported by the 1867 sketch map of Bellville, Livingston and Thornton's "*River Shire from Lake Nyassa to the sea*". This (Figure 4.2), and other historic maps are placed in a later chapter (4), as it is there where they are used to illustrate historical channel change).

[33] 'Nyanza', meaning 'a great body of water', especially a lake; Mukulu, meaning 'large'

"*At the north-eastern end of the marsh, and about three miles from the river, commences a great forest of palm trees (Borassus aethiopum*[34]*). It extends many miles, and at one point comes close to the river. ... The mountain range, which rises close behind the palms, is generally of a cheerful green, and has many trees, with patches of a lighter tint among them, as if spots of land had once been cultivated*."

One of the few published photographs of the Elephant Marsh from the mid-19th century taken by Kirk shows the *Borassus* palms (Figure 2.2). It is likely that earliest surviving photographs from the interior of tropical Africa are those taken in the Lower Shire and Zambezi Valleys between 1858 and 1862 by Kirk (McCracken, 2008). A drawing of the lower Shire[35] River by Johnston (circa late 19th century) is reproduced in Figure 2.3.

Upstream of the Marsh and north of the palms,[36] the morphology changed, and the Livingstones provide the following accounts of the river and activities:
"*Beyond the marsh the country is higher and has a much larger population. We passed a long line of temporary huts on a plain on the right bank, with crowds of men and women hard at work making salt. They obtain it by mixing the earth, which is here highly saline, with water, in a pot with a small hole in it, and then evaporating the liquid, which runs through, in the sun. From the number of women we saw carrying it off in bags, we concluded that vast quantities must be made at these works*..."
"*Above the palm-trees a succession of rich low islands stud*(s) *the river. Many of them are cultivated, and grow maize at all times of the year, for we saw it in different stages of growth; some patches ripe, and others half grown, or just sprouting out of the ground. The shores are adorned with rows of banana-trees, and the fruit is abundant and cheap. Many of the reedy banks are so intertwined with convolvulus and other creepers as to be absolutely impenetrable..."*
"*The large village of the chief Mankokwe occupies a site on the right bank;*[37] *he owns a number of fertile islands, and is said to be the Bundo, or paramount chief of a large district..."*
"In passing the Elephant Marsh [on our return journey down the Shire] we saw nine large herds of elephants; they sometimes formed a line two miles long."

An invaluable hand-drawn sketch by Johnston[38] (1898) of the Shire River channel between Chiromo and Chikwawa (refer to Section 4.1.1, Figure 4.5 and Figure 4.6) supports the above descriptions, some of which are also illustrated in the 1867 sketch map of Bellville, Livingston and Thornton (refer to Figure 4.2). These include the forest of palms that colonised the north-western side of the Marsh, and a more elevated floodplain upstream of the Marsh where many villages were located and extensive cultivation took place. For example, Johnston's 1898 map shows the positions of eight villages along the river banks between the Marsh and Katunga, including, Mtshenga's, MaKwira's, and Masea's.[39] Also indicated are banana trees, palms (including coconut and phoenix) and the positions of

[34] Palm tree with a tall 'lollipop' growth form. The *Borassus aethiopum* species, according to a local taxonomist, and inferred from the distribution given by Palgrave and Palgrave (2002). This species may be confused with *Hyphaene petersiana*, but the latter has a less likely distribution in Malawi.
[35] a more specific location for the drawing is not known
[36] The northern or upstream extent of the marsh in the mid-1800s differs from its current extent - this is discussed in Section 4.1 'Historical channel change and flooding'
[37] The right bank as the expedition was travelling upstream, but the left bank using 'river terminology' (i.e., facing downstream)
[38] Sir Henry Harry Hamilton Johnston was a British explorer, botanist, linguist and colonial administrator - one of the key players in the 'Scramble for Africa' that occurred at the end of the 19th century. In 1889 Johnston was sent to Lisbon to negotiate the Portuguese and British spheres of influence in south-eastern Africa, then went to Mozambique as consul. From there he went to Lake Nyasa to resolve the war between Arab slave-traders and the African Lakes Trading Company. The map is signed/dated by Johnston/1898 although he left British Central Africa in 1896 (https://en.wikipedia.org/wiki/Harry_Johnston, accessed 02/09/2016). Possibly, the map pre-dates 1898 and/or was not drawn by Johnston personally.
[39] These are referred to in their diaries.

confluences of the Mwanphazi, Maperera and Mwanzi Rivers.[40] Mankowe's village is not indicated on Johnston's map, but is shown a short distance downstream of the Mwanza River confluence on Livingstone and Arrowsmith's 1865 map, and on the Belville *et al.* 1867 map (refer to Section 4.1.1). No great "*great forest of palm trees*" is evident today, but a few scattered plants occur (Figure 2.4).

Figure 2.2 Photograph of the Elephant Marsh by Kirk circa 1859 (after Dritsas, 2010)

Figure 2.3 Drawing of the Shire River by Johnston, indicating *Borassus* palms, papyrus and elephant grass (after Johnston, 1891)

[40] These have been invaluable for ~geo-referencing the sketch map.

Figure 2.4 **Photograph (September 2015) taken from the north of Lake Tomaninjobi and facing north-west, showing scattered palms in the distance and the Thyolo Mountains beyond, which Livingstone described in 1859; for location reference 'a' refer to Figure 4.11 in Chapter 4**

The wood-cut engravings from the Livingstonia Mission (1877) reproduced in Figure 2.5 provide further evidence for the palm tree forest in the Elephant Marsh stretching away from the river at its northern end ("*The Last of the Elephant Marsh*"). A wide channel is also evident (Johnston (1898) notes channel widths between 50 and 100 yards[41]) at this location.

After the grounding and sinking of the *Ma-Robert* in the Kongone River in December 1860,[42] a new steamer, the *Pioneer* arrived early in 1861 (Figure 2.6). Unfortunately, the *Pioneer* performed below expectations: Livingstone had requested a vessel with a draft of three feet, but the Pioneer drew five feet. The *Pioneer's* first venture[43] up the Shire River was lengthy and challenging, with much effort required to haul the vessel off sandbanks. Chibisa's,[44] near the foot of the Kapachira Falls, was only reached in July 1861.

"*The Pioneer is I am sorry to find much too deep for river work. We observed that in the Rovuma* [River] *- and again when we reached the upper part of the Elephant Marsh. Below that she has plenty of water. We warped her up some 20 or 30 miles in order to place the missionaries and our men in a healthy spot at Chibisa's* ..."[45]

It was during this 1861 Shire trip that severe fever broke out among the crew as the vessel "*ploughed its way through the Elephant Marsh*". On its return to the Zambezi River in late 1961, the Pioneer was grounded for five weeks on a shoal.[46]

In a letter thought to be dated 26 September 1961,[47] Livingstone notes the following about the morphology at the upstream end of the Marsh:
"*At the upper part of the Elephant Marsh the Shire branches out so that we could not get five feet for the Pioneer, below that it is all deep and above the cataracts it is all deep*..."

[41] 46 to 91 m
[42] the southern branch of the Zambezi River through its delta
[43] March 1961
[44] Also spelt Tshibisa's and Shibisa's
[45] Livingstone, David, 1813-1873. Letter to John Washington, 6 December 1861. Images copyright National Museum of the Royal Navy. As relevant, copyright Dr. Neil Imray Livingstone Wilson. Creative Commons Attribution-NonCommercial 3.0 Unported (https://creativecommons.org/licenses/by-nc/3.0/).
[46] sandbank or sandbar
[47] Livingstone, David, 1813-1873. Letter to (probably) George Denman, 26 September 1861. Images copyright The Fitzwilliam Museum, University of Cambridge. Images reproduction by permission of the Syndics of the Fitzwilliam Museum, Cambridge. Images protected by UK copyright law. Creative Commons Attribution-NonCommercial 3.0 Unported (https://creativecommons.org/licenses/by-nc/3.0/).

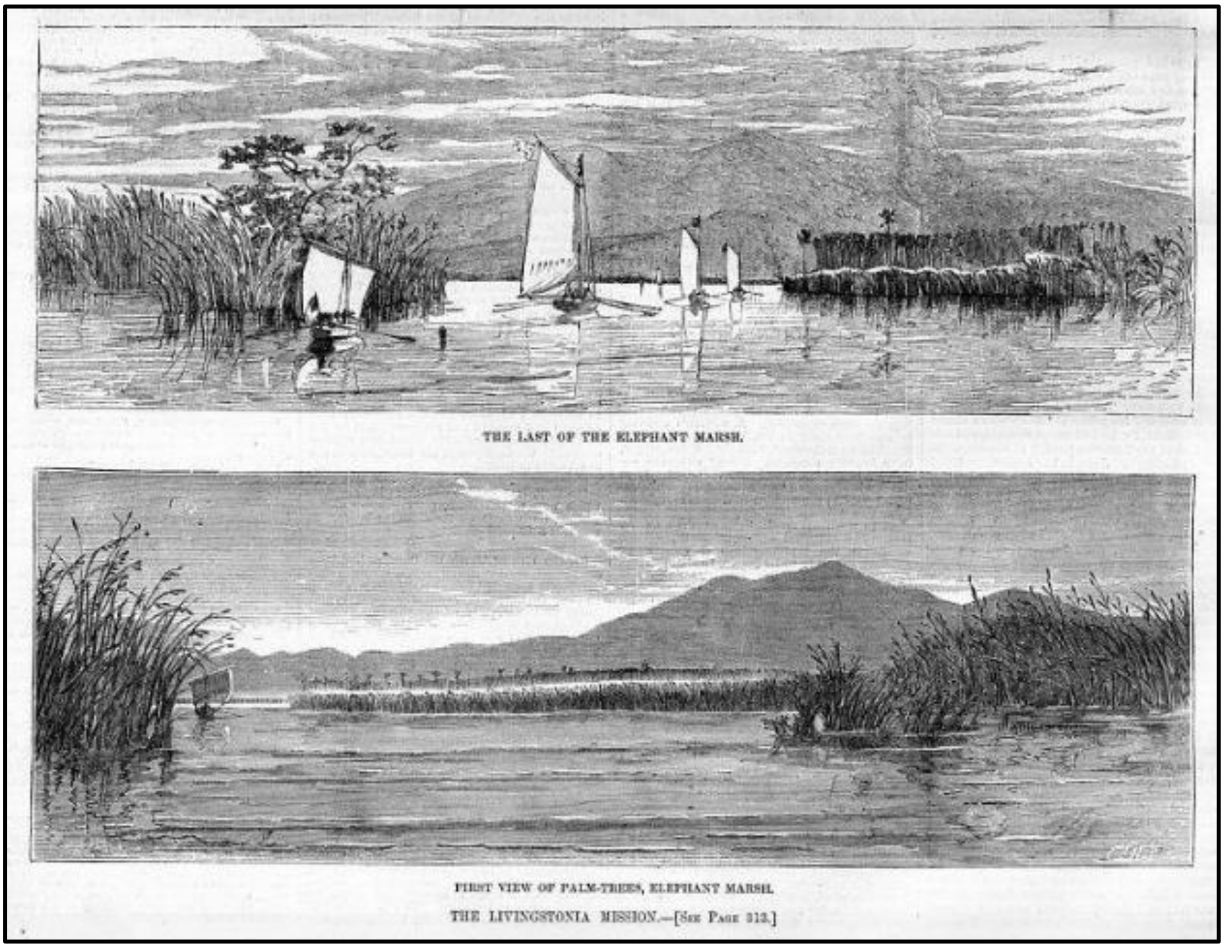

Figure 2.5 Wood-cut engravings published in Harper's Weekly (April 1877) entitled, top: "*The Livingstonia Mission - The last of the Elephant Marsh*" and bottom: "*First view of palm-trees, Elephant Mars*h"

Numerous channel bifurcations are also drawn on Johnston's 1898 channel-planform map, at the position where the "*End of the Elephant Marsh*" is indicated. More significantly, the following additional annotations are included at this location: "*palm forest begins*" and the "*Gombwe* I[d] [island]". This allowed the northern extent of the Marsh, as at the mid-to-late 1900s, to be accurately positioned (see Section 4.1.1, which deals with the mapping of historic channel change).

The *Pioneer* made two further trips up the Shire: one in 1862, and; a final voyage in 1863 towing Livingstone's twin-screw iron steamship, the *Lady Nyasa,*[48] to Chibisa's. This was Livingstone's last trip up the Shire; he was stranded in the Marsh for weeks where fever beset his crew and contributed to Thornton's death. During this period, Livingstone wrote numerous letters from the Marsh, the first pages from two of these are reproduced in Figure 2.7. The following transcript, taken directly from a letter dated 20 February 1963,[49] describes the difficulty experienced in towing the *Lady Nyasa* through the Marsh, followed by an optimistic note - an expression of his undefeated spirit throughout the Zambezi expedition.

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[48] financed personally by Livingstone and destined for Lake Malawi; the Lady Nyasa was assembled at Shupanga on the banks of the Zambezi River, *sans* its boilers

[49] Livingstone, David, 1813-1873. Letter to Robert M. Livingstone, 20 February 1863. Images copyright National Library of Scotland. Creative Commons Share-alike 2.5 UK: Scotland (https://creativecommons.org/licenses/by-nc-sa/2.5/scotland/). As relevant, copyright Dr. Neil Imray Livingstone Wilson. Creative Commons Attribution-NonCommercial 3.0 Unported (https://creativecommons.org/licenses/by-nc/3.0/).

"*In ascending this river with the Lady Nyasa in tow alongside, we had no difficulty till we got to the Elephant Marsh, and there in sudden bends we found it an awkward matter to get along, for two vessels cannot be turned so quickly as one, and Lady Nyasa being pretty deep would go aground, and was very difficult to get off. Further up the river had risen only one foot eleven inches instead of about three feet, so we have lost more time than we anticipated. But no important work is ever accomplished without considerable trouble*."

The challenge of skippering these two steamers through the Marsh was also noted by Thornton, expressed below in an appended note to his published letter to Murchison (Thornton, 1864):
"*He*[50] *overtook the steamers [the Pioneer and Lady Nyasa] on the 28th of January near the 'Elephant Marsh' on the Shire, and accompanied them in their slow progress amongst the shoals of that much-obstructed river until February 13th*... ".

Kirk (1865)[51] described a similar picture:

- Feb. 1st: "*On Monday last we steamed on to the middle of the Elephant Swamp and there stuck. There was no passage of 4 ft to take us through. We have had a week's hauling in the meantime. It is strange to find in the middle of the rainy season the water of the Shire is no higher than in the June of the former year*".
- Feb. 7th: "*Still in the middle of the Elephant Swamp*"

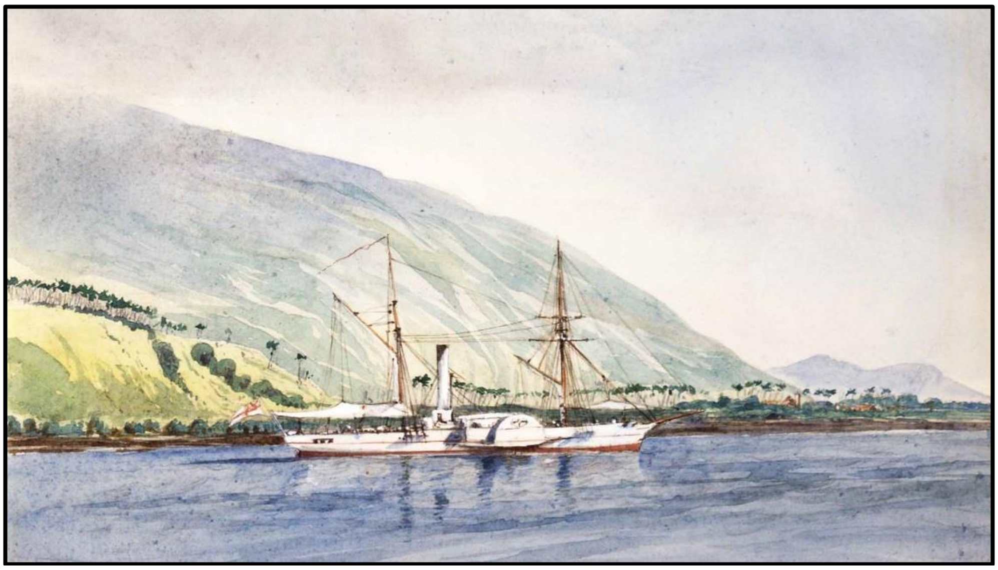
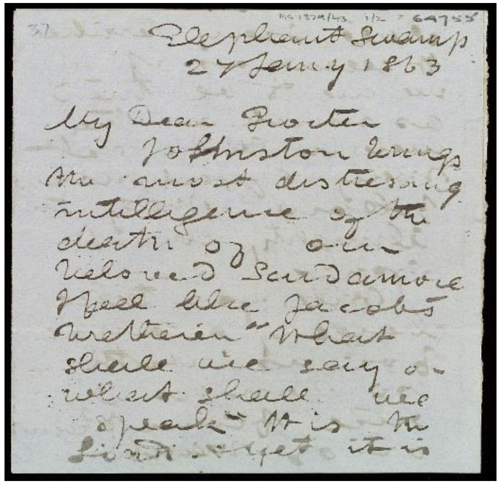


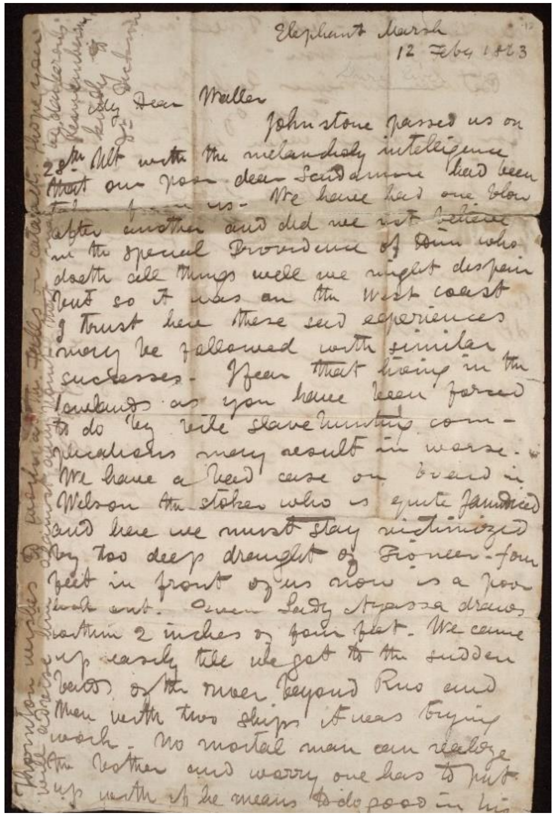
Figure 2.6 Livingstone's river steamer, the *Pioneer,* at anchor in Pomony Harbour, Johanna,[52] 1862[53]

[50] Thornton, travelling in his own boat
[51] as cited by Garland and Killick, 1994
[52] Anjouan (also known as Ndzuwani or Nzwani, and historically as Johanna or Hinzuan) is an autonomous island in the Indian Ocean that forms part of the Union of the Comores.
[53] courtesy of the Smithsonian Libraries, Washington, D.C.



Elephant Swamp
27 Jany 1863

My Dear Procter
Johnston brings
the most distressing
intelligence of the
death of our
beloved Scudamore
I feel like Jacob's
brethren "What
shall we say or
what shall we
speak" It is the
Lord & yet it is



Elephant Marsh
12 Feby 1863

My Dear Waller
Johnstone passed us on
28th Ult with the melancholy intelligence
that our poor dear Scudamore had been
taken from us. We have had one blow
after another and did we not believe
in the special Providence of Him who
doeth all things well we might despair
but so it was on the West coast
I trust here these sad experiences
may be followed with similar
successes. I fear that living in the
lowlands as you have been forced
to do by vile slave hunting com-
plications may result in worse.
We have a bad case on board in
Wilson the stoker who is quite jaundiced
and here we must stay [illegible]
by too deep draught of Pioneer - four
feet in front of us now is a poor
look out. Even Lady Nyassa draws
within 2 inches of four feet. We came
up easily till we got to the sudden
bends of the river beyond Ruo and
then with two ships it was trying
work. No mortal man can realize
the bother and worry one has to put
up with if he means to do good in his

Figure 2.7 **Livingstone, David (1813-1873). Letters written from the Elephant Swamp/Marsh, left: to Lovell J. Procter, 27 January 1963,[54] and right: to Horace Waller, 12 February 1863.[55]**

[54] Images copyright Wellcome Library, London. Creative Commons Attribution 4.0 International (https://creativecommons.org/licenses/by/4.0/). As relevant, copyright Dr. Neil Imray Livingstone Wilson. Creative Commons Attribution-NonCommercial 3.0 Unported (https://creativecommons.org/licenses/by-nc/3.0/)
[55] Images copyright National Library of Scotland. Creative Commons Share-alike 2.5 UK: Scotland (https://creativecommons.org/licenses/by-nc-sa/2.5/scotland/). As relevant, copyright Dr. Neil Imray Livingstone Wilson. Creative Commons Attribution-NonCommercial 3.0 Unported (https://creativecommons.org/licenses/by-nc/3.0/)

At the date of Livingstone's final trip up through the Elephant Marsh, he wrote to the Editor of the Medical Times and Gazette, in reply to a pejorative article (5 July 1862) entitled "*English Sacrifices in Central Africa*".[56] This poetic description alludes to the quality of flow through the Marsh, which Livingstone compares to the situation in London.

"*Horror seems to lay hold on you at the bare mention of' 'Elephant Swamp'. I am actually to pass through it tomorrow, and am only sorry that the enormous herds of elephants - we have seen eight hundred in it at once - have become so knowing we have no chance of getting a steak or a foot. ... my imagination ... obstinately pictures you sitting on that wilderness of eight hundred cesspools ... and drinking water ...with all the abominations and unutterable filthinesses which are poured out of Oxford, Reading, etc., into your cup. Oh! you filter your water through a few inches of sand, do you? I would not trust it ... though filtered through the Great Sahara. The delicious unconsciousness with which you exclaim 'Elephant Marsh'; good heavens! what a vista of deep swamp, rotting vegetation, flies, vermin, stinks, agues, and dysentery do the words call up! only excite a merry laugh, which I beg you to believe has not one particle of ill nature in it, ... You have actually a larger area of cesspool and marsh around and above London than exists in the Elephant Swamp, and to the direful effects let typhus, typhoid, diphtheria, cholera, consumption, scrofula, etc., testify. Here they are absolutely unknown*."

Livingstone's *Lady Nyasa* never steamed into Lake Malawi as he intended, since the expedition was withdrawn later that year before the Murchison bypass was completed for portage of the dissembled *Lady Nyasa*. Livingstone left Chibisa's in 1864 when the Shire River had risen sufficiently, and both the *Pioneer* and *Lady Nyasa* left the Zambezi's waters. Livingstone returned to Nyasaland and Lake Malawi in 1865, but not *via* the Zambezi and Shire Rivers.

Livingstone believed that the East African rivers were the gateway to central Africa, and his Zambezi Expedition was partly tasked with finding this route, involving journeys up the Zambezi, Shire and Ruvuma Rivers. Though in this respect the mission was unsuccessful, his explorations pioneered the river route into Malawi which was used for several decades. Livingstone's expeditions generated numerous written descriptions and maps of the areas through which he passed, and their value in providing a window to the character of the Elephant Marsh, over one-and-a-half centuries ago, have been invaluable to this study.

2.2 Other accounts from the late 19th century

Three other 19th century descriptions of the Marsh are sourced from Pringle's Universities Mission to Central Africa; as part of Lieutenant Scaler's[57] descriptions of routes and districts in southern Nyasaland; and Grogan and Sharpe's "*From the Cape to Cairo*".

In a colourful narrative of an interestingly entitled "*A Journey in East Africa towards the Mountains of the Moon*"[58] Pringle (1886) describes her ascent through the Elephant Marsh in September three years earlier, in a leaking boat:
"*We had not the faintest conception how long it would take us to get out of the Elephant Marsh, far less what was to be the length of our voyage. ... At length we descried a grove of palm-trees, a welcome sight, for we were sure they must be beyond the marsh; so after all, if the boat did sink, it would not*

56 Livingstone, David, 1813-1873. Letter to Editor of the Medical Times and Gazette, 26 and 27 January 1863.
57 assistant to Johnston - refer to Footnote 38
58 'Mountains of the Moon' is an ancient term referring to a legendary mountain or mountain range in east Africa at the source of the Nile River (Wikipedia). The intention of including these "*much-confounded mountains by way of a title*" was to hint as it not being solely about missions.

be quite up with us. All we had now to guard against was sticking on sand-banks. This was not very easy, because the river was getting full of shallows, and in some places the men had to get out and wade before they could push the boat along. Every now and then we came to a dead halt; and as we got off again, we heard the boat grating along the bottom of the river. Notwithstanding this, our leak was not getting perceptibly larger. We have learnt now how the steamer became worn out in about a year's time, and now this boat is almost in the same condition. Sometimes, when we start in the morning, we see a group of palms or some other landmark, and in the evening find it has taken us a whole day to reach it ...”

“*There were no more thickets of papyrus now, because we had done with the mud and reached gravel. One of the small lakes or nyanjas we came through was actually called Nyanja ya Matope. Litope would mean a puddle or a little mud; but the plural, matope must mean a tremendous quantity. ... matope was turning into makande; and we expect, when we return here, to find so much ground dry and well makandemised, that, if the boat should leak again, we can land and trot about anywhere*.”

Of particular relevance from Pringle’s account is the description of the grove of palm trees, taken to indicate the upstream end of the Marsh; and the reference to the small lake they travelled through called ‘*Nyanja ya Matope*’. No other references have been found referring to lakes, lagoons or ponds located specifically in the Marsh,[59] and the seasonal nature of these lakes, is also noteworthy.

Some ten years later in 1893, Lieutenant Scaler published in the Geographical Journal some descriptions of the Shire River and surrounding area between Chiromo and Chikwawa - a further window into the character of the area a few years before the turn of that century:
“*Chiromo lies in the fork at the confluence of the Ruo and the Shire. The Shire here is about 70 or 80 yards broad, with a current of from 2 to 4 miles an hour,[60] varying according to the season. The Ruo forms an estuary nearly 200 yards wide for the last mile before it reaches the Shire*.”

“*From Chiromo to Chikwawa, a distance of 45 miles as the crow flies, and about 70 miles by the river, a boat or canoe takes from three to five days to ascend, and from a day to a day and a half to descend. Steamers and lighters drawing more than 15 inches of water cannot get up in the dry season (from July till December); in the wet season, however, there is a depth of from 3 to 4 feet of water. For the first few miles above Chiromo the river is broad, and in the dry season there are several dangerous sandbanks. For the next 20 miles the Shire flows through the Elephant Marsh, and is split up into several narrow and deep channels. The natives from the surrounding villages raise splendid crops of maize on the islands in the marsh, and also a little rice. The whole marsh is* [e]*specially suitable for rice cultivation. Above the marsh the river passes through fine belts of palm-trees. About 50 miles above Chiromo, on the left bank,[61] lies Makwera's village, where there is a considerable population. Makwera has three coconut-palms in his village which bear nuts every year; he has also a fair number of sheep and large herds of goats. ... About 10 miles higher up is the village of Masea, on the right bank, but before reaching this the confluence of the Maperera on the left bank is passed. This river forms the boundary between the West Shire District and Makwera's country. ... On the right bank before reaching Masea's the confluence of the Mwanza and Shire is passed, but I have never been able to locate this point exactly, owing to the numerous islands in the main channel of this river. Masea is one of the Makololos left in the country by Livingstone. His chief remembrances of Livingstone are connected with the steam launch Ma Robert, of which he was stoker, and with a trip he made in her to the Johanna*

[59] The Livingstones (1893) description refers to the “*Shire marshes*”, which include the Ndinde Marshes downstream of Chiromo
[60] 0.9 to 1.8 m/s
[61] Reference to banks are correct - i.e., facing downstream.

Islands. Masea is now the most important of the Makololo chiefs. ... Both on the Shire and the Mwanza the country is fairly thickly populated. ... Opposite Masea's village, on the left bank, the Blantyre Mission have lately opened a station in connection with their steamer on the river. About 5 miles further up on the left bank is the station of the African Lakes Company and the village of Katunga. .... The African Lakes Company's steamers land their cargo for Blantyre at Katunga. The Government station is at Chikwawa, about 2 miles further up on the same bank[62] ..."

Scaler's 1893 descriptions of the river corroborate those of Livingstone (1859 to 1864), and with information derived from Johnston's (1898) mapping of the river and villages along its course. The Shire River depths given by Scaler are lower than can be inferred from Livingstone's river journeys based on the draft of the steamers brought through the Marsh. There is evidence in the form of Lake Malawi levels (refer to Figure 1.8) to suggest that the Shire River experienced substantially higher flows during Livingstone's journeys than towards the end of the 19th century. A few other points worth noting are references to the large (human) populations along the Shire River between Chikwawa and the Marsh, members of which farmed undoubtedly not only islands, but also the fertile floodplains. Within the Marsh itself, maize is noted on the islands, as is the cultivation of rice.

The following extract from Johnston's 1897[63] description of the Marsh is for a period with declining and low Lake Malawi levels in the late 1890s[64] (**Figure** 2.16) and is the first portrayal of a largely dry landscape:
"*A short distance above the Ruo one enters the Elephant Marsh, district of great grassy flats, flooded occasionally when the Shire River overflows its banks, but ordinarily a dry level stretch of prairie dotted with pools of water. At the close of the dry season, when the tall grass has been burnt down, and there is little or no cover for the game to hide in, it is really a remarkable spectacle, as seen from the deck of a steamer, to watch the great herds of big animals wander over these savannahs in search of the young verdue springing up amid the charred stubble of the old grass*."

In "*From the Cape to Cairo*", Grogan and Sharpe's (1900) account of their November 1898 journey between Chiromo and Makwira's, they describe the Elephant Marsh as being " *...a large tract of country lying on the left bank of the Shire...* ". Although no other physical descriptions of the Marsh are given, this is nonetheless useful, since it supports the mapped position of the Shire River, relative to the Marsh, from (at least)[65] the mid-1900s and for most of the 20th century. Further detail is presented in Section 4.1.1, 'Historical channel change'.

2.3 A brief description of river and railway transport relevant to the Marsh

Ever since Livingstone's pioneering voyages, the Shire River near the Marsh features prominently in accounts of developing transport routes into central Malawi. In this section, descriptions of transport infrastructure and routes relevant to the Marsh were compiled from numerous sources, including Gamlin (1935), Pike and Rimmington (1965), Perry (1969), MacGregor-Hutcheson (1969), Boeder (1980), Garland and Killick (1994), Nkana (1999), Kalinga (2012) and Callighan (2012). Also included is an account of the history of the infamous Chiromo Bridge and its flanked embankments. These structures are considered to have substantially influenced the morphology of the lower reaches of the

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[62] There is evidence that Chikwawa was previously located on the opposite bank to its current position. Bamford (2009): "*The map also showed Chikwawa as being on the eastern bank of the Shire on the flood plain opposite its current site on the cliffs*."
[63] cited by Jawali, 2015
[64] Johnston declared Nyasaland (today's Malawi) the British Central Africa Protectorate, and he was made its first commissioner in 1891.
[65] Livingstone's Expedition provides the earliest information

Elephant Marsh, and the issues around the Chiromo Bridge and its associated embankment are still very much of current interest. Historical photographs sourced for this study also provide valuable support of more quantitative analyses - described later in this report.

Landlocked Malawi has its closest access to the sea, from its southern border, through Mozambique. Consequently, the country's earliest (documented) links with the outside world developed from the south, with river steamers operating the 290 km between Chinde (at the Zambezi River mouth) and Chiromo for three decades. These included not only the early steamers such as *Ma Robert*, *Pioneer*, *Itala,*[66] *Lady Nyasa II*[67] and *SS*[68] *Stevenson*, but also gunboats such as the *HMSs Herald*[69] and *Mosquito* that patrolled the Lower Shire. The vessels on the lower Shire reached large numbers; by 1923 ALC's fleet comprised seven ships and numerous barges, and the British Central Africa Company (BCAC) was running five ships in addition to its barges.[70] A report from 1896[71] records the number of vessels calling at Chiromo that year: 113 steamers, 196 barges, 97 boats and 139 canoes. Until 1900 all steamers travelled as far as Katunga, but declining Shire water levels (refer to Figure 1.9) meant that after the turn of that century, the larger steamers stopped at Chiromo, and later Port Herald, 48 km downstream. At Chiromo, passengers and goods destined for Blantyre and Zomba were transferred to smaller boats (e.g., as illustrated in Figure 2.5), and taken a further 80 km to Katunga. From there, a regular service of porters was operated to carry goods up the escarpment while passengers continued by foot or by sedan chair.[72]

In 1900, navigation difficulties on the Shire River resulted in a proposal for the Shire Highlands Railway (SHR) from Chiromo to Blantyre. When construction commenced in 1904, the railway was extended south to Nsanje due to further declining flows. There were disputes between Sharpe[73] (including his consultants and traders using the river), and the SHR Company over bridge construction at Chiromo: the latter favoured narrow spans that would not allow passage of any steamers, whilst Sharpe and the traders insisted on longer spans and sufficient clearance to enable the largest steamers[74] to clear the structure. Sharpe and the Crown agents succeeded, and the infamous Chiromo Bridge[75] was completed in 1907 and opened in 1908. The earliest definitively-dated photograph of the bridge (circa 1908 to 1918) is reproduced in Figure 2.8, and indicates the opening span alongside the left bank (about one-third of the channel width). The towering structures flanking the opening section were presumably for elevating the opening span. Interestingly however, although it is stated that it would take a dozen men 30 minutes to raise and lower the movable section using a winch, there is also reference to the lifting mechanism never having been installed! A high quality photograph of the bridge construction is reproduced in Figure 2.9, entitled "*Chiromo Bridge in southern Malawi, under Reconstruction and Restructuring",* but is undated. Although the title (reconstruction/restructuring) appears to refer to a later date, it was more likely taken during construction (circa 1904 to 1907), since the structural elements appear new and no flood damage (refer to next paragraph) is evident. The

[66] The *Ilala*, named after the place where Livingstone died, carried the Livingstonia Mission Party onto Lake Malawi in 1875; it drew 3 feet of water and was designed in sections that could be carried individually - 600 porters were recruited to carry the dissembled vessel around the Murchison (Kapachira) Rapids (http://www.ccapsolinia.org/blog/2015/07/21/the-ilala/, accessed 5 September 2016)
[67] Launched in 1879 it was the first commercial steamer between Chinde and Katunga, and the forerunner of the ALC fleet.
[68] Steam Ship
[69] from whence 'Port Herald' (present day 'Nsanje'), the point of entry to Nyasaland, received its name
[70] Other companies involved with river transport were Sharrer's Zambezi Traffic, and Oceana Consolidated.
[71] a "*better depth of water*" was noted for this year
[72] a chair or windowed cabin suitable for a single occupant, carried by at least two porters in front and behind, using wooden rails that pass through brackets on the sides of the chair
[73] succeeded Sir Harry Johnston in 1896 as (first acting then) Commissioner of the British Central Africa Protectorate; later was Governor of the Nyasaland Protectorate
[74] 114 ft (35 m)
[75] 400 ft: 10 spans with one opening section of 100 ft

caption may also be referring to final replacement of temporary bridges that were constructed from 1904, to transport material, and removed each year as the river rose and became navigable.

The bridge lasted four decades until "*in 1948 an island of water vegetation*[76] *released from the Elephant Marsh by heavy rains surged down the Shire River and washed away the Chiromo Bridge. This ill-timed disaster severely damaged export trade for the following year, and a ferry service, even more vulnerable to the vagaries of African conditions, was brought back into operation. ... Throughout 1949 a new railway Bridge was constructed*, ...".[77] Based on the 1952 date of the photograph reproduced in Figure 2.10, and the fact that there is no further reference to (major) reconstruction in the available literature, it is reasonable to conclude that the 1950 bridge is the same three-span structure existing today (refer to Figure 2.11). The bridge is downstream of its 1908 alignment, with the remaining left-bank winching structure and the original elevated embankment discernible in the photographs.

No mention is made of damage to the embankment in 1952[78] but four years later, floods associated with Cyclone Edith washed away part of the embankment near Chiromo (Pike and Rimmington, 1965; Callighan, 2012). In 1977, the rail bridge was adapted into a combined rail/road, with the intention of "*ending the ferry service across the Shire River*",[79] illustrated in the photograph reproduced in Figure 2.12. It is not entirely certain when floods first damaged sections of the railway embankment between the towns of Bangula and Chiromo: all references[80] are to the 1997[81] floods having caused collapse/s (from breaching and washaways as depicted in Figure 2.13). Satellite imagery for mid-1989,[82] however, indicates a breach eight years earlier on the Bangula side. What is clear is that motorised vehicular transport across the Shire River at Chiromo ceased in at least 1997, and that ferrying was again necessary (Figure 2.14). This continued for ~17 years until 2014, when a temporary bridge[83] was constructed across the most substantial breach at Mtayamoyo, and other sections were filled-in (with culverts).

[76] sudd
[77] Callighan (2012)
[78] Pike and Rimmington (1965) give the Shire's and Ruo's (1952) discharges as 850 and 2 000 m^3/s, respectively; Ruo's (1956) discharge at 5 400 m^3/s
[79] Kalinga, 2012
[80] e.g., MCA, 2009; https://en.wikipedia.org/wiki/Bangula, accessed 08/09/2016; www.engineeringnews.co.za/print-version/work-on-malawi-roadrail-bridge-to-start-soon-2003-09-12, accessed 08/09/2016
[81] World Vision report 25 February 1997: "[The] *lower portion of the massive Shire River in southern Malawi* [was last week declared] *a disaster area. An estimated 80,000 Malawians and 20 000 Mozambican refugees were made homeless by persistent rains and resultant flooding that began hitting southern Malawi the second week of February. Thousands of mud huts and even some sturdy, modern houses crumbled after being partly submerged in water. More than 20 persons were also feared dead in Chikwawa district, most of them reportedly perishing while trying to swim across rivers that had broken their banks*." (http://reliefweb.int/report/malawi/world-vision-malawi-floods-project)
[82] The largest (measurement-based) peak for the period 1976 to 2009 occurred in 1989 (refer to Figure 3.8), relief work by international organisations (refer to http://m.reliefweb.int/report/35534/malawi/malawi-floods-mar-1989-undro-situation-reports-1-3, accessed 7 September 2016)
[83] named Mtayamoyo meaning death trap - refer to http://timesmediamw.com/mtayamoyo-bridge-from-death-trap-to-life-saver/, accessed 08/09/2016; also, refer to http://joycebanda2014.org/?m=201403&paged=2, accessed 08/09/2016

Figure 2.8 “***Bridge over the Shire River on Nyasaland Railway, showing recent diminution of river***” **after Sharpe (1918)**

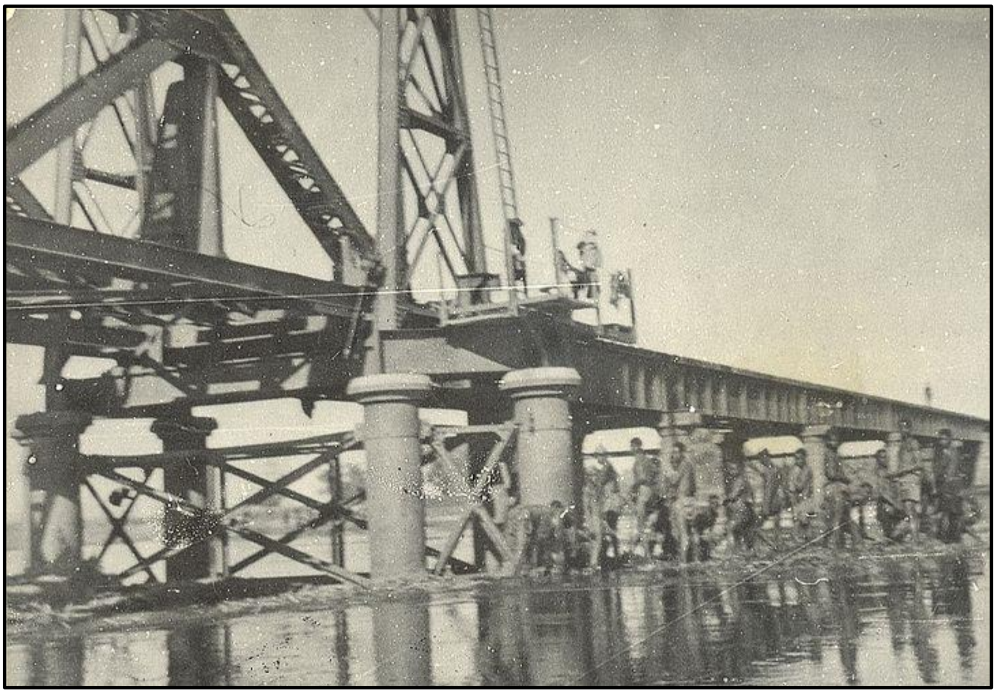

Figure 2.9 “***Chiromo Bridge in southern Malawi, under Reconstruction and Restructuring***”, **from the National Archive of Malawi (undated)[84]**

[84] https://commons.wikimedia.org/wiki/File:Chiromo_Bridge_under_Reconstruction_and_Restructuring.jpg

Figure 2.10 **"*The flood of February, 1952, at Chiromo. In foreground on the right is the Ruo River – 'Rhodesia Herald' photograph*", after Richards (1954)**

Figure 2.11 **Flooding of the Elephant Mashes in January 2015; looking west across the Chiromo Bridge (photograph credit: Julien Lefevre/Medecins Sans Frontiers)[85]**

[85] https://www.theguardian.com/global-development/gallery/2015/jan/21/malawi-floods-cause-devastation-in-pictures

Figure 2.12 “***The Shire River at Chiromo looking downstream: the Ruo River joins the Shire River from the left bank just beyond the palm trees***”**, after Pike and Rimmington, 1965**

Not even a year later, in January 2015, devastating floods hit the lower Shire; the temporary (Mtayamoyo) bridge and the sections of repaired embankment were washed away, and; the Ruo River changed its course and confluence with the Shire River (refer to Figure 2.15 and Figure 4.24). The Ruo breached it banks, but unlike after previous recent large floods (e.g., 2001), flow did not return to its pre-flood (low flow) channel. The river, which was the Malawi-Mozambique border (which follows the Ruo’s old course), now flows in a north-westerly direction directly into the Marsh through Lake Tomaninjobi. The town of Chiromo has become isolated by rivers, and the informal ferrying of people and their goods across the Shire River is back once more.

With reference to Chiromo, Garland and Killick (1994), wrote:
“Flooding has caused much human distress in the Chiromo district and at various times exceptional floods have caused a great deal of damage. ... Chiromo peninsula, a narrow levee thrown up by the Ruo River at its junction with the Shire, must always have been a good tactical place for a settlement [viz. Chiromo town], with rivers on two sides and mountains not far behind, though also extremely vulnerable to floods.”

The Chiromo Bridge and its damaged embankments are current concerns for several reasons: there are transport difficulties across the Shire River; Chiromo Village is now separated from the rest of Malawi by the Ruo and Shire Rivers with no bridge crossings, and the breached embankments and altered course of the Ruo have potentially major consequences for the hydromorphology of the Elephant Marsh, which are discussed later in Section 4.1.1.

Furthermore, there are considerations of engineering the Ruo River to return it to its pre-2015 course, which would require the construction of (further) embankments to separate it from the Marsh.

Figure 2.13 Collapse of the rail line caused by breaching and washaway of the supporting embankment

Figure 2.14 Ferrying of people and goods in wooden boats across the Shire River at a breach in the embankment, circa 2006

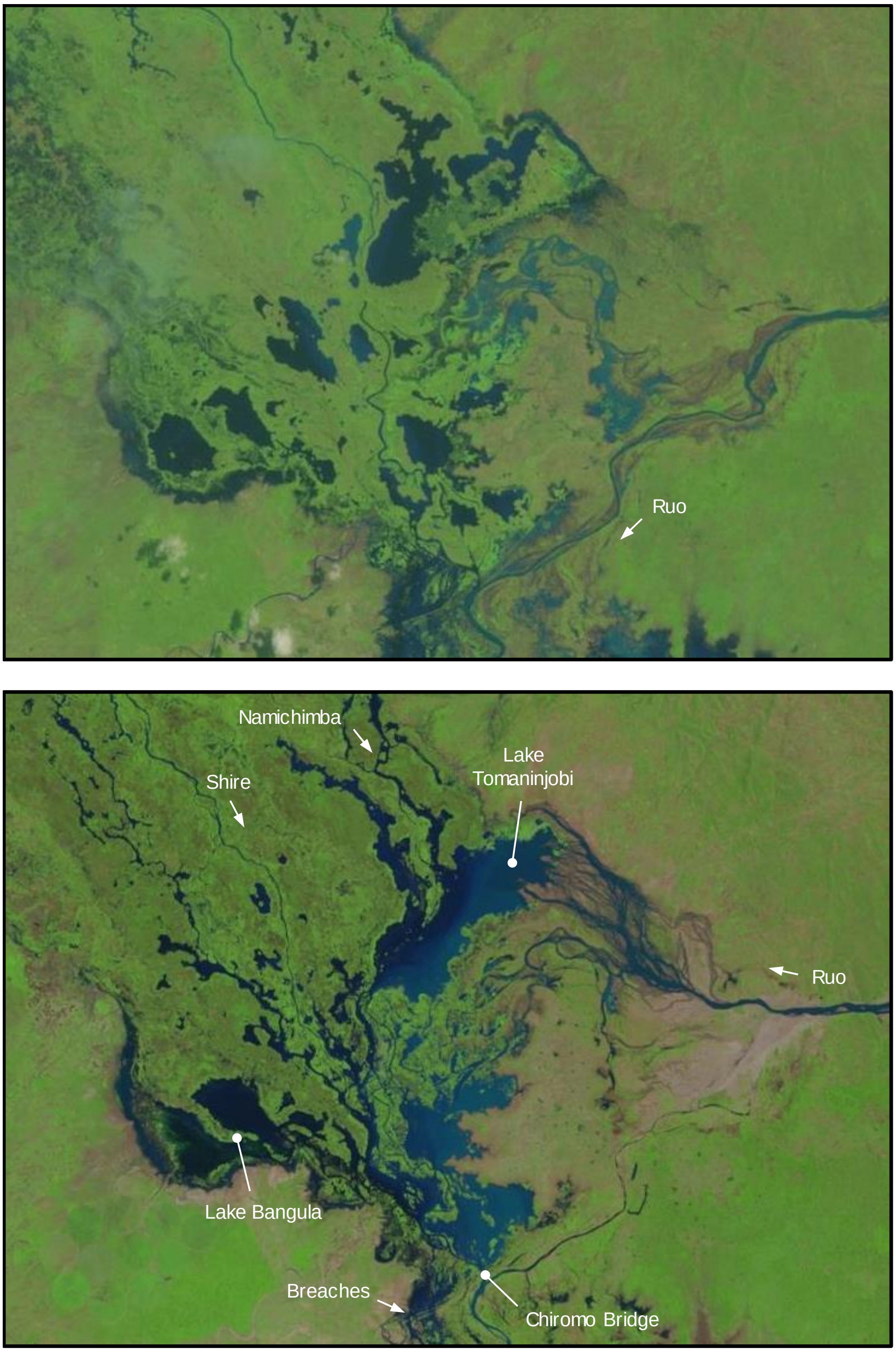

Figure 2.15 Landsat[86] satellite imagery of the downstream portion of the Elephant Marsh, showing the course of the Ruo River after the 2001 (top) and 2015 (bottom) floods

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[86] source: USGS EarthExplorer (http://earthexplorer.usgs.gov/)

In the article "*Journey through time: The Chiromo moonlight picnic*", Garlick and Killick (1994) describe other aspects of the Shire River:

"*It seems the Shire is completely blocked now at Alumenda, about ten miles south of Sucoma.[87] In any case most of the flow seems to go down the Namichimba where the river divides above Sucoma and this naturally causes much concern on the estate. ... Before the Shire was blocked at Alumenda the tankers used to fill up at Sucoma then travel down past Chiromo to the Zambesi [River] and Chinde*."

"*Then by a sudden change, typically African, Chiromo's fate was sealed. The [Shire] river level dropped exceedingly low, so low that people could walk across the Shire in places*..."[88]

This 'sudden change' or variability was most recently demonstrated by the 'failed' wet season of 2015/16[89] which followed the devastating floods one year earlier.

2.4 More-recent insights from the Shire Valley Project

Another useful source of information for this study has been the Shire Valley Project (SVP) about which a two-part retrospective recently was written by Welsh (2013; 2014). The SVP originated as a major integrated development scheme of the Nyasaland Protectorate's colonial government in the 1940s. It combined two objectives: regulating Lake Malawi levels, and; controlling flows through the Shire Valley. It was conceived in terms of a hydrological system in dynamic equilibrium: seasonal flows into the lake would be released in a timely manner to allow permanent and controllable releases into the Shire River throughout the year. This would allow stabilisation of the lake; expansion of water transport; generation of hydro power; establishment of a vast irrigation programme in the lower Shire Valley;[90] and the prevention of flooding. In short, the SVP was intended to "*revolutionise the economy of Nyasaland*".[91]

Richards, chief engineer of the SVP during the mid-1900s, described the SVP and its purpose during a presentation to the Nyasaland Society and other attendees, which was published in 1954. In this presentation, he described the flow conditions in the Shire River and Marsh in the first decades of the 20th century:

"*As the Lake fell [*from 1896 to 1915], *so the flow down the Shire River decreased year by year and during the wet seasons the tributaries in flood deposited banks of sand and silt in the main channel of the Shire. On these reeds grew and gradually consolidated the banks. Year by year further sand and silt was deposited on these banks until eventually they became so large as to block completely the Shire channel and to stop all flow. This happened early in 1915 and thereafter there was no flow down the Shire except that produced by its tributaries in the wet seasons*."

"*With its outlet blocked the lake started to rise gradually and in about 1933 began to overtop the silt banks which were blocking its channel. These banks were gradually washed away, the great growth of reeds in the channel was cleared and by about 1937 there was again a broad deep channel from the lake downwards*."

"*During the years when the Shire had ceased to flow a remarkable state of affairs existed. At Liwonde, where there is now a broad deep stream, the whole channel was filled with reeds. The same was to be seen at Matope while in the lower river, that is the river downstream of Chikwawa, enormous areas*

---

[87] Nchalo Sucoma Sugar Estate

[88] in referring to the end of the 19th century

[89] This had negative consequences in this study for monitoring suspended sediments during high flows - refer to Section 6.2.2.2

[90] Richards (1954), states the following, which aptly describes the thinking at that time concerning the value of aquatic ecosystems: "*Reclamation of swamps will restore to agriculture areas of fertile land, now useless. Some of this land, such as that in the lower river, is said to be the most fertile in Nyasaland. This reclamation will first be effected by improvements to the river channel*." Interesting use of the adjectives "*reclamation*", "*restore*", "*useless*" and "*improvements*". Maxwell (1954) describes it as follows: "*We hear of wonderful land in the Elephant Marsh that is to be saved*..."

[91] Colby, 1956 as cited by Welsh, 2013

which are now a mere[92] *swamp covered with dense reeds were under cultivation, rice, cotton and maize being grown*."
"*During the wet season these areas were flooded by the flow of the tributaries and as the water receded cultivation commenced. During the dry season the river was so low that ... and to drive a car through a few inches of water at Chiromo. ... was able to construct a road right across the Elephant Marsh from Alimenda*[93] *to the east side and there was a road running along the bank of the Shire from Chiromo to Chikwawa*."
"*With the rise of the Lake and the sweeping away of the bars across its channel, all this area reverted to swamp and marsh and it still remains in this state*."

Several of these observations are significant for this project, namely: the cessation of flow along the Shire River in the early part of the 20th century; the suggestion that, even a century ago, sediment loads were not inconsequential;[94] cultivation in the Elephant Marsh; and the reverting of cultivated areas to swamp and marsh when the hydrological regime changed.

Maxwell (1954) penned a retort to Richards' (1954) description of the SVP, which included his own experiences:
"... *but the next stage to Chiromo by shallow draft side paddle steamer was difficult with many stoppages on sand banks. From Chiromo to Katunga's (Chikwawa) travel was by shallow draft barge called a house boat. This was in April* [1902] *and I am certain that the water in the river did not exceed eighteen inches"*.
"... *Throughout that journey* [in 1904 from Chikwawa to Chiromo by a new road that had been constructed] *there was no sign of any marsh land and the Shire river was not visible at any point. There can be no doubt that that road was constructed to take the place of river for transport purposes* ..."
"*During the early part of 1907 I was in Chiromo for some time and did a lot of shooting far into the Elephant Marsh and never found a trace of water or any indications of marsh, while the land was very ordinary indeed. By this time the transport from Chindi to Port Herald was all by canoes and small boats and then by railway to Chiromo*."
"... *I contend that flow of water down the Shire river never ceased between years 1916 and 1937 and I trust I have proved that the same thing happened in 1903*..."

Although ambiguous, Maxwell is basically saying that Shire River ceased flowing from 1904 to 1916 and not from 1915 to 1933 when Richards says flow ceased. Importantly, the two agree that flow in the Shire stopped. A possible reason for the discrepancy is that Richards refers to lake outflow and Maxwell refers to the Marsh. There may have been lag effects due to groundwater/evaporative losses, sediment deposits blocking lake outflow (refer to Section 2.5); and tributary inflows on the rising limb of lake levels from 1916. The durations, however, are reasonably comparable. The exact period is not particularly important for this study, and the sourced historic photographs showing people wading across the Shire River at Chiromo Bridge, circa 1908 to 1926,[95] support both sets of dates. Hydrometric station history notes for Chiromo (circa 1975) state: "*Both rivers Shire and Ruo were dry at [their] confluence during the dry seasons of 1922 and 1926*."[96] The descriptions of "... *no sign of marsh land*..." in 1904 and "... *never found a trace of water or any indications of marsh* ..." in 1907 are also invaluable to this study.

Maxwell posed two insightful questions concerning the SVP and operation of the (proposed at that time) barrage. Firstly, with reference to Richards' "*reclamation*" of the "*useless*" swamps, he asked

[92] refer to Footnote 90
[93] Also spelt 'Alumenda' - refer to Figure 4.6
[94] with subsequent colonisation by vegetation, which in turn leads to reduced conveyance, etc.
[95] Figure 6.16
[96] Atkins (2012) data archive; original data source not given (station only opened mid-1900s)

how SVP would reconciled flooding of lake shore areas if the swamps are to be "*to be kept dry*" as this would mean that sluices cannot be opened during wet periods of high lake levels. Presumably this was anticipated through "*improvement*" of the Shire River (through the Marsh and elsewhere) to provide the necessary channel conveyance to prevent inundation of the adjacent landscape. The potential success of such an engineered adaptation of a low gradient sediment-laden river with a flow regime characterised by extreme (unmanageable) floods is questionable. In any event, the lower Shire River was never "engineered" and it is unlikely, at best, that any attempt to do so would have kept the floods depicted in Figure 2.10 and Figure 2.11 in a confined channel. Maxwell's second enquiry essentially was one about the effect of climate change. He asked how flow regulation during dry periods (such as experienced in the early 1900s) could supply sufficient flow for hydropower production, when in his words, "... *water cannot be got out* [of the lake] ...". In time, the fluctuations of Lake Malawi have been recognised as a sensitive indicator of regional climate change (Nicholson, 1998), the influence of which, on livelihoods, is a key reason for the Elephant Marsh Project.

These historical accounts are supported by the water-level observations at Lake Malawi mentioned in the Introduction (1.3), which show the total cessation of flow in the early 1900s to the highest (measurement-based) annual outflow of ~850 m^3/s, and; by the earliest hydrological studies (e.g., Sieger, 1887; Dixey, 1924; Lamb, 1966; Pike, 1968a) of Lake Malawi, which highlighted the sensitivity of Shire River outflows to the subtle balance between rainfall and lake evaporation. The next section relates these historical descriptions of flow through the Marsh with these more quantitative measures of Shire River flows.

2.5 Lake level fluctuations

Recorded lake levels for the period 1896 to 1963 are plotted in Figure 1.8, and extended to 2014 in Figure 1.9. Probable levels between 1860 and 1896, compiled from various historical sources by Latham (1960), are also shown in Figure 1.8. Prior to 1896, there is considerable evidence in the form of observations by earlier travellers,[97] indicating that lake level fluctuations have persisted for a considerable time. Using this evidence Dixey (1924)[98] suggested that the lake levels were very low in 1830, very high in 1857 to 1863, high in 1873, falling in 1875 to 1878, high in 1882, and very low in 1890. Of particular interest to this study is the level of ~474.0 m noted for "Livingstone" (Figure 1.8), which translates[99] into an unregulated discharge of ~220 m^3/s.

Thus, there is evidence to support the occurrence of a low lake level period (and by inference low to no flow in the Shire River) in the early 1800s and historical accounts are unequivocal that flow ceased in the early 1900s. It is thus possible that these low-flow periods are the result of infrequent, but predictable, climatic phenomena.

Nicholson (1998) produced chronologies of level fluctuations for Lake Malawi and Lake Chilwa, building on the records compiled by Sieger (1887), Lamb (1966), Pike (1968a), Drayton (1979), Crossley *et al.* (1984), Owen *et al.* (1990) and others. He compared these with famine and drought chronologies from areas of Malawi, Zambia, Zimbabwe and Mozambique in relatively proximity to the drainage basins of the two lakes.

Figure 2.16 shows the lake chronology from 1800. According to Nicholson (1998), the lake was almost certainly low throughout most of the first few decades of the 19th century, and probably towards the

[97] *viz*. Livingstone, Dr Laws, F. Moir, Rev Janson and Archdeacon Johnston
[98] as cited by Pike, 1968a
[99] applying the unregulated or capacity rating curve (Norplan, 2013)

end of the 18th century as well. This was supported by traditions of severe droughts and dry rivers; the location of villages, later flooded, suggests the lake stood at least 9 m below modern levels (Owen *et al.,* 1990).[100]

Nicholson (1998) also provided a 1 200-year chronology based on a synthesis of published archaeological, geological and historical information and new historical climate chronologies for the region (refer to Figure 2.17). The record provided good detail of fluctuations during the last six centuries, with available evidence demonstrating that within the last one or two millennia, fluctuations of at least 14 m occurred in the lake. Extending this to the lake history, Delvaux (1995) cites fluctuations as much as 250 to 400 m - this being consequence of, *inter alia,* natural climate change.

Nicholson's (1998) study raises a number of relevant points for this study, namely: historically-low lake levels, low enough to terminate outflow to the Shire River, are not infrequent phenomena: four are indicated in the last 900 years, three in the last 470 years and two in the last 200 years; their frequency has increased in more recent times; whilst three have similar minima, the penultimate occurrence in the 1700/1800s, for which there is "*unquestionable*" evidence,[101] was substantially lower and of longer duration.[102]

The caption to Figure 2.16 refers to the build-up of a sandbar in the Lake, which is also indicated in Figure 1.8. Its significance is mentioned here because of its effect on the outflow from the lake into the Shire River. Pike and Rimmington (1965) give the following explanation:
"*In 1915, when the lake reached its lowest recorded level, all flow in the Shire River ceased except in the wet season, and bars of sand and silt overgrown with reeds were formed at the mouths of the main tributaries. The main barriers were at the outlet of the Lake, at the north end of Lake Malombe and at the confluence of the Nkasi River, south of Lake Malombe. These bars contained the water of Lake Nyasa [Malawi], the water level [of] which rose considerably between 1915 and 1934. Early in 1935, however, the water began to rise over the bars and flow down the Shire River was resumed, its volume increasing until it reached a maximum flow in 1937.*"

These dates support Richards' (1954), rather than Maxwell's, period of flow cessation during the early 1900s, but as mentioned previously, refer to conditions at the lake outflow. A further regulation (before operation of the Kamuzu Barrage) that affected lake outflow was the so-called 'bund' constructed across the Shire River at Liwonde in 1956. This was done on the premise that the lake level was declining. During the wet season of 1956/57, however, the level rose rapidly, and the bund was artificially breached to prevent the inundation of lake shore areas. The artificial dam created by the bund prevented any outflow between September 1956 and August 1957 (Pike, 1968a) - refer to Figure 1.9.

The next Chapter deals with the quantitative hydrology of the Marsh, necessary for developing the hydrodynamic model, which is presented in Chapter 5.

[100] as cited by Nicholson, 1998
[101] Nicholson, 1998
[102] many decades

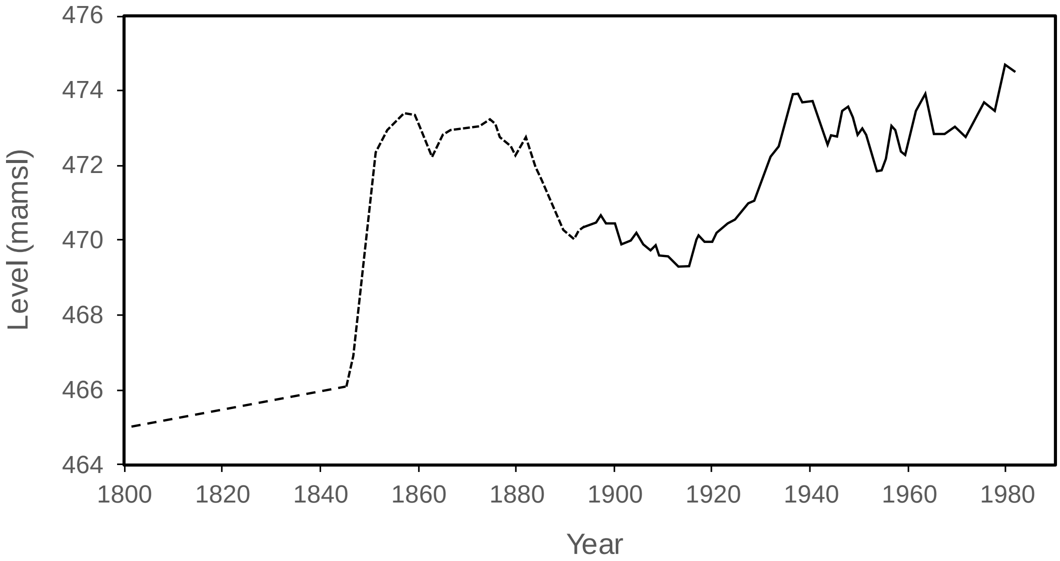

Figure 2.16 "***Fluctuations of Lake Malawi [water level] since 1800 based on historical and geographical information and, beginning in 1896, modern records. Long-dashed lines indicate general periods of low levels; short-dashed lines indicate trends based on proxy data; solid lines indicate the modern lake record. Modern data are corrected for a build-up of a sandbar in the lake***" **(redrawn from Nicholson, 1998)**

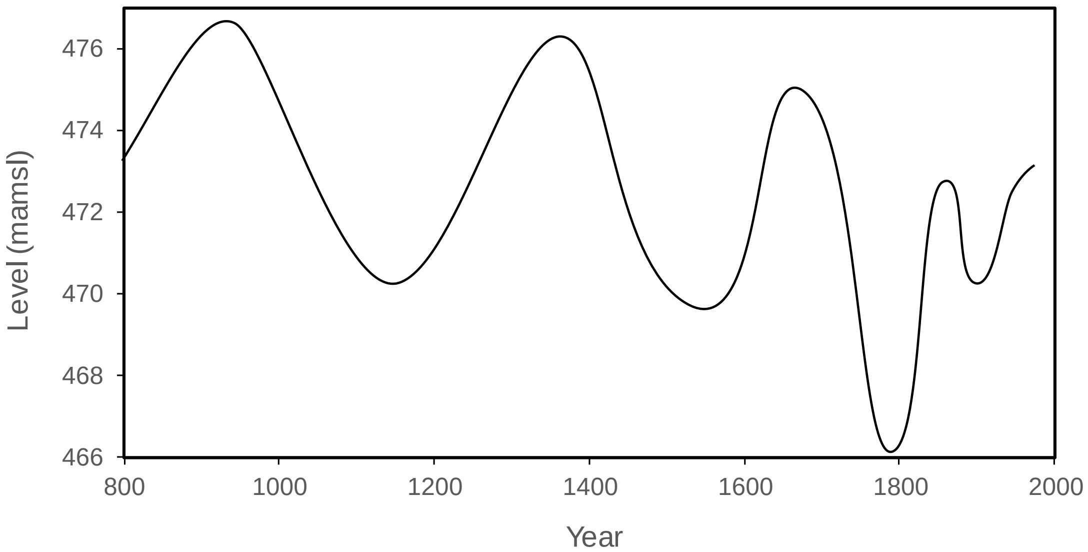

Figure 2.17 "***Long-term fluctuations of Lake Malawi***" **(redrawn from Nicholson, 1998)**

3 Hydrology of the Marsh

An understanding and quantification of the hydrological behaviour of the Marsh is necessary for the development, calibration and application of the hydrodynamic model presented in Chapter 5. Furthermore, it is preferable to develop models on measured[103] rather than modelled data as this significantly reduces the underlying uncertainties.

3.1 Background, data collation and review

The Shire River and its sub-catchments adjacent to the AOI are illustrated in Figure 3.1. The catchments and rivers were digitised using the 1 arc-second version (typically 30 m resolution) of the Shuttle Radar Topography Mission (SRTM)[104] Digital Elevation Model (DEM), which was recently[105] released for Africa. The SRTM DEM is, however, of insufficient vertical accuracy in areas of flat relief to allow accurate[106] digitisation of river planform. The Water Resource Units (WRUs)[107] adjacent to the AOI (specifically 1F, 1G, 1H, 1L and 14 (Ruo)), were divided into sub-catchments for this study.

It was anticipated[108] that historical records from the national gauging network would be used in this study, with no need for in-depth data collation, review and analyses of hydrological information. This was based on the fact that many other projects involving hydrological data had already been completed, including: the National Water Resources Master Plan (NWRMP; 1986); Kumambala (2010); the Water Resources Investment Strategy (WRIS; Atkins and Wellfield, 2011); Atkins (2012) and JIKA (2014).[109] Atkins' (2012) 'Integrated Flood Risk Management' project report also included[110] details of data obtained for hydrometric stations used in that study that were used for Table 3.1. Further to this, Kumambala (2010) indicated that there were minimal missing data for the two most-critical stations at Chikwawa and Chiromo, for 12 and 45 years of record, respectively (Table 3.2). It therefore followed that the hydromorphological study could largely use existing and previously synthesized hydrological data, with minor updates through more recent records, where available.[111]

In contrast to these expectations, the procurement and synthesis of daily data was an enormous challenge.

103 since the data are not 'measured' *per se*, but derived from measurements
104 refer to http://srtm.usgs.gov/
105 latter part of 2014; previous versions were ~90 m resolution
106 Inaccuracies in Figure 3.1 include the Ruo River, which is shown as flowing directly into the marsh (presently the case, but not in February 2000 when the mission took place and the Shire-Ruo confluence was downstream of Chiromo Bridge); the Shire's channel/s flowing through the marsh; and the Nkombedzi Wa Fodya (sub-catchment 1H2) which flows directly into the marsh at its north-western end and not into the Mwanza River (sub-catchment 1K) as shown.
107 Atkins (2012); available from the Malawi Spatial Data Portal (MASDAP) at http://www.masdap.mw, accessed 13/09/2016
108 as outlined in the project proposal and inception reports
109 Japan International Cooperation Agency
110 in the Appendix
111 The location of historically-active hydrometric stations at Chikwawa and Chiromo, with none in-between, made this river stretch the obvious choice for defining the upstream-downstream AOI, even though the Marsh's upper boundary is a considerable distance (~35 km) downstream of Chikwawa.

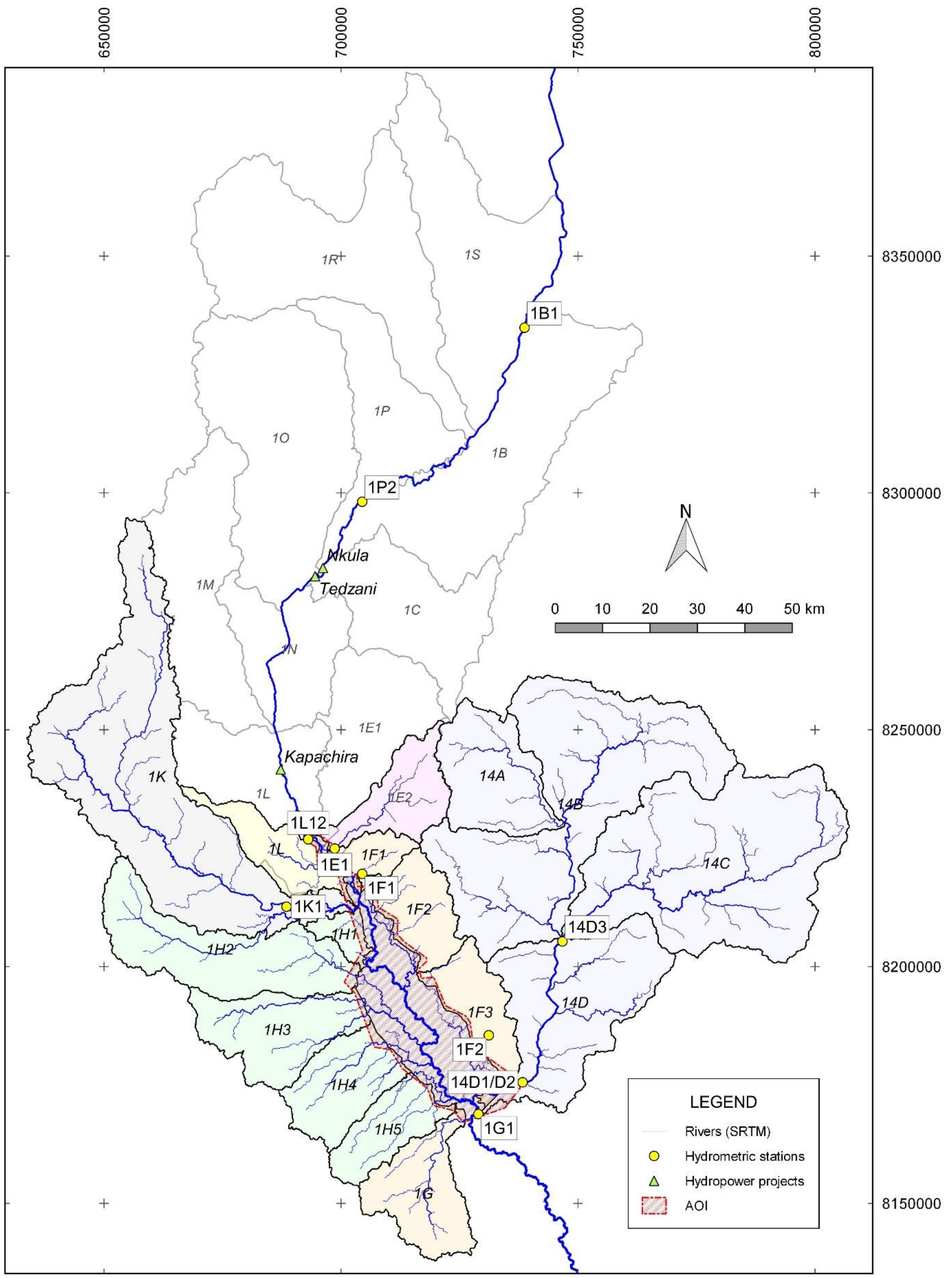

Figure 3.1 **The Shire River, tributaries and sub-catchments adjacent to the Marsh (shaded) and upstream; the position of hydrometric gauging stations of relevance to this study and hydropower projects; the Area of Interest (AOI) incorporating the Marsh, between Chikwawa (1L12) and Chiromo (1G1) is shaded red; CRS is Arc 1950 (Malawi)**

Table 3.1 Selected gauging stations and variables monitored, as listed in the Atkins (2012) flood risk management study

Gauge		Chart data	Rating history[1]	Water level		Average daily flow	Ratings[2]	Spot gaugings[3]
Number	Name			Twice daily	Daily average			
Shire River								
1B1	Liwonde	√	√	√	√	√	√	√
1P2	Matope	√	√	√	√	√	√	√
1L12	Chikwawa		√	√	√	√	√	√
1G1	Chiromo		√	√	√	√	√	√
1G3	Tengani		√		√			
1G2	Nsanje				√			
Tributaries of the Shire flowing into the Marsh								
1E1	Mwanphanzi at Pokonyola		√					
1F1	Maperera at Mfumbi							
1F2	Thangadzi East at Gooke	√			√	√	√	√
1F20	Nkhata at M'modzi						√	
1K1	Mwanza at Tomali		√	√	√	√	√	√
Ruo River								
14D3	Sandama			√	√	√	√	
14D2	Sinoya	√	√	√	√		√	
14D1	Sinoya South		√	√	√	√	√	√

Lightly-shaded rows indicate critical stations for this study, [1]generally refers to maintenance and re-establishment of gauge plates; [2]refers to rating equations; [3]refers to measurements of stage and discharge

Table 3.2 Gauge records and missing data for critical gauges given by Kumambala (2010)

Gauge		Record	Missing data (%)
Number	Name		
1G1	Chiromo	1953 - 1998	3.7
1L12	Chikwawa	1978 - 1990	2.5
14D1	Sinoya South	1981 - 1990	8.7

Daily hydrological data sets[112] were initially obtained from project archives and concurrent SRBMP consultancies, including: WRIS (Atkins and Wellfield, 2011); Atkins (2012, 2015); JIKA (2014); NIRAS and directly from the Ministry of Irrigation and Water Development (MoIWD) in Lilongwe.

[112] extracted from both the HYDSTRA and HYDATA databases

Discharge time-series from completed and concurrent SRBMP projects were inappropriate for use here, since for these studies[113] a monthly time-frame is deemed sufficient.

As a first step, daily discharge time-series from these different sources were compared. The comparison revealed substantial differences between records for the same station, as well as between stations after 1992. Furthermore, data for the stations downstream of Kamuzu Barrage, which are most critical for this study[114] (1L12 at Chikwawa and 1G1 at Chiromo; Table 3.1 and Figure 3.1), were found to be the most inaccurate. This necessitated a detailed assessment of available hydrological data and required that station records further upstream (Matope and Liwonde) and downstream (Tengani and Nsanje) also be considered.

Unfortunately, the records from the downstream stations were not useful as they reflected the difficulty of recording water level[115] and inferring discharge in the morphologically dynamic and flood-prone lower Shire River. Indeed, the main reason for the discrepancies between HYDSTRA and HYDATA records[116] was the use of rating equations after 1992, derived from data[117] for earlier periods. This applies mainly to stations in the lower Shire River. The daily discharge time-series sourced could therefore not be used in this study, and further synthesis of observed records was necessary.

From the available information listed in Table 3.1, the critical information required for further analyses was:

- stage time-series;
- ratings (or stage-discharge relationships), including:
    - dated measurements (spot gaugings),
    - and equations[118] with dates of applicability.

These data were sourced[119] and are discussed in the next section.

3.2 Stage time-series data and ratings

3.2.1 Shire River

The record lengths for the stage time-series and rating measurements, the missing data and number of observations (stage and ratings, respectively) are given in Table 3.3. Figure 3.2 provides plots of the ratings, including sourced measurements and continuous relationships developed in 2010 by the Surface Water Division of the Department of Irrigation and Water Resources (MoIWD).[120] A brief description of each hydrometric station is provided below.

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[113] The Atkins (2012) 'Integrated flood risk management' study involved daily and event-related time scales, but no time-series data could be sourced; other concurrent projects though requiring daily or instantaneous discharges, do not require lengthy time-series.
[114] although the hydrology of the Ruo River is also important for the Marsh's southern region.
[115] also referred to as 'gauge plate/board' or 'stage plate/board'.
[116] HYDSTRA and HYDATA are time-series data archive and management system software, commonly used in the water resources field.
[117] measured stage-discharge or 'spot gaugings' as referred to in Table 3.1
[118] generally fitted by regression to rating measurements
[119] initially from the Atkins (2011, 2012) data archives and through Atkins (2015); later this study obtained personally from the MoIWD in Lilongwe
[120] from the Atkins (2011) data archive

Table 3.3 Hydrometric record summary for selected stations along the Shire River

Gauge		Stage		Ratings	
Number	Name	Record length	Missing (%)	Record length	Observations
1B1	Liwonde	01/01/1951-29/06/2016	4.4	10/11/1989-20/10/2008	101
1P2	Matope	03/01/1953-31/10/2005	4.4	14/11/1978-23/09/1990	122
1L12	Chikwawa	07/05/1977-21/11/2009	13.9	22/07/1977-12/12/1998	211
1G1	Chiromo	02/01/1953-31/12/2009	3.0	13/11/1979-07/09/1998	167

3.2.1.1 Station 1B1 (10201) at Liwonde

Station 1B1 (10201) at Liwonde has been described as one of the most important primary gauging stations (NWRMP, 1986). It was installed in 1948 at a site downstream of the (then) ferry crossing. In 1965/66 the Kamuzu Barrage was constructed, and Station 1B1 is now located a few hundred metres downstream thereof. A water-level recorder was installed in 1953. Of the four gauges listed in Table 3.3, Liwonde has the longest, up-to-date stage record. Figure 1.4 shows the scatter in the rating data, which is largely due to temporal changes in the stage-discharge relationship.[121]

3.2.1.2 Station 1P2 (11602) at Matope

Station 1P2 (11602) at Matope was opened in 1952 and is located at a pool upstream of a bend in the river with a natural downstream hydraulic control (refer to Figure 3.3). It included a cableway to facilitate the measurement of discharge, particularly useful for high flows. Ratings are in the discharge range 279 to 960 m^3/s and display minimal scatter (Figure 3.2). A single rating function is well correlated with the measurements, but has been extrapolated down to zero flow - the basis for which is unknown. This extrapolated curve is inaccurate, and provides discharges ~150 m^3/s lower than calculated upstream at Liwonde. The rating function has therefore been modified in this study to provide more reasonable estimates based on flow continuity from upstream.[122] The stable downstream hydraulic control (refer to Figure 3.4) supports temporal extrapolation of the rating function (i.e., pre-1978 and post-1990). According to Atkins (2015), this station is operational, although no data for the past decade could be sourced.

3.2.1.3 Station 1L12 (11212) at Chikwawa

Station 1L12 (11212) at Chikwawa was opened in 1977 and is at the Kamuzu Bridge (Figure 3.5).[123] The NWRMP (1986) notes: "*Results of discharge observations at this site are not in conformity as there are significant variations between water levels and flow*". This is exemplified by substantial scatter in Figure 3.2, largely[124] due to morphological changes in the alluvial river (refer to Figure 6.18).[125] Measured data are between 100 and 3 048m^3/s.[126]

[121] ascertained by differentiating between the hydrological years
[122] with emphasis on the dry season where the relative flow contributions from intervening tributaries are small
[123] noted as an important primary station (NWRMP, 1986)
[124] also inaccurate measurements
[125] Atkins, 2011 (supporting compiled station notes), note the general increase in levels/flows from 1995 to 2000 which they state needs to be checked as genuine and not a function of rating change - no further reference to this was found in the accompanying report.
[126] This appears to be an outlier and may be inaccurate - the next highest measurement is 2 088 m^3/s

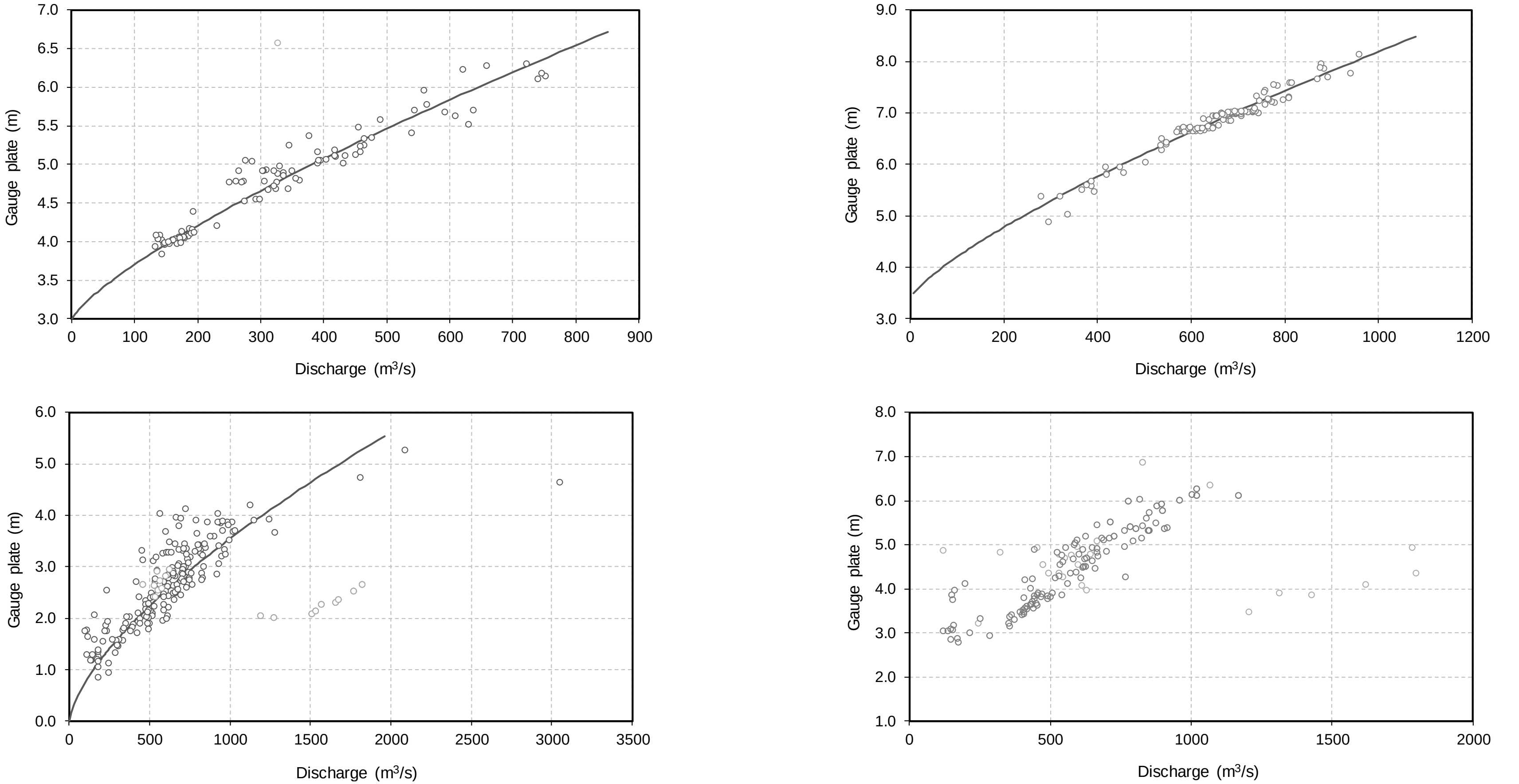


Figure 3.2 Rating data and functions,[127] top-left: Liwonde, top-right: Matope, bottom-left: Chikwawa, bottom-right: Chiromo[128]

[127] Surface Water Division of the Water Resources Department, MoIWD (2010)
[128] Lightly-shaded markers (all stations) indicate rating data of low confidence (inferred from time-series plots, e.g., refer to Figure 3.7)

Figure 3.3 Aerial view of Shire River at the Matope Station 1P2[129]

Figure 3.4 View of the rapid looking upstream from the bridge over the Shire River at Matope (refer to Figure 3.5)

[129] source: Google Earth

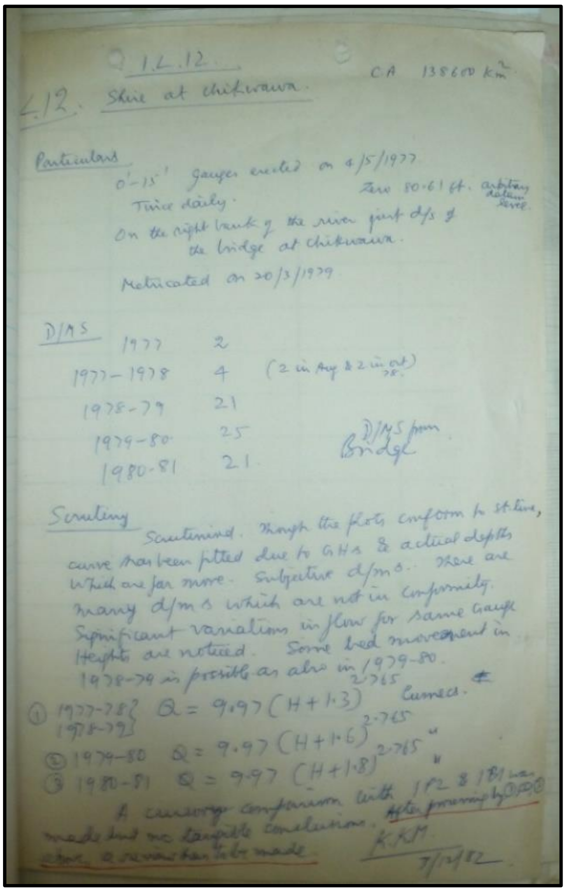
The Atkins (2012) data archive contains a series of five (hand-drawn) rating curves covering the period 1977 to 1997, thus recognising temporal changes in the station's rating. The general trend indicated by the ratings, over the 20-years, is a reduction in level of ~0.5 m (for equivalent discharges). The 2010 'update' (refer to Footnote 127) and more recently obtained data,[130] however, provide a single rating function. The Atkins (2012) data archive also includes valuable 'station history notes', an example of which, for Chikwawa, is reproduced in Figure 3.6. It is dated 1982, and notes: "*Significant variations in flow for the same gauge heights are noticed. Some bed movement in 1978/79 is possible as also in 1979/80.*"

3.2.1.4 Station 1G1 (10701) at Chiromo

Station 1G1 (10701) at Chiromo is another primary gauging station for this study as the railway embankment represents a partial[131] downstream boundary in the hydrodynamic modelling of the Elephant Marsh (Chapter 5), and historical records from Station 1G1 are essential for model calibration. It was installed between 1947 and 1952 (NWRMP, 1986) and is located at the Chiromo Bridge (Figure 3.5). A water level recorder was installed in 1957.

Figure 3.5 Historic photographs[132] of gauge stations with plates fixed to bridge piers, left: Chikwawa (1L12) located at the Kamuzu Bridge (1979), and right: Chiromo (1G1) at the railway bridge (undated, circa 1970/80s)

[130] HYDATA obtained from the MoIWD, 2015
[131] the other downstream boundary is at the breached railway embankment through which the Shire's alternate right-bank channel passes
[132] Atkins (2011) data archive



1.L.12.

L.12. Shire at Chikwawa.

C.A 138600 km²

Particulars

0'–15' gauges erected on 4/5/1977.

Twice daily.

Zero 80.61 ft. arbitrary datum level.

On the right bank of the river just d/s of the bridge at Chikwawa.

Metricated on 20/3/1979

D/MS

1977	2	
1977–1978	4	(2 in Aug & 2 in Oct 78.)
1978–79	21	
1979–80	25	D/MS from Bridge
1980-81	21	

Scrutiny

Scrutinised. Though the plots conform to st. line, curve has been fitted due to GHs & actual depths which are far more. Subjective d/ms. There are many d/ms which are not in conformity. Significant variations in flow for same Gauge Heights are noticed. Some bed movement in 1978-79 is possible as also in 1979-80.

① 1977-78 / 1978-79 $Q = 9.97 (H+1.3)^{2.765}$ Cumecs.

② 1979-80 $Q = 9.97 (H+1.6)^{2.765}$ "

③ 1980-81 $Q = 9.97 (H+1.8)^{2.765}$ "

A cursory comparison with 1L2 & 1B1 was made but no tangible conclusions. After processing by ①, ②, ③ a review has to be made

K.K.M. 7/12/82

Figure 3.6 **Example of a ’station history note’[133] for Chikwawa (1L12), dated 1982**

The NWRMP (1986) notes:

“*The discharge measurements are affected by the Ruo River levels and errors are inevitable during the flood stages in [the] Ruo River. Analysis is based on the water levels at 1G1 and the combined flow of Shire at 1G1 and Ruo River upstream of its confluence with the Shire River. The data can be considered as fairly good though discrepancies are inevitable in any analysis and study of Shire flow in its entire stretch from Chikwawa downstream*.”

This statement describes a serious shortcoming regarding this gauge’s location but is not clear. The analysis is based on the water level at 1G1, which includes the backwater effect of the Ruo River, to the extent that flow reversal has been noted (e.g., Pike and Rimmington, 1965) at the bridge when the Ruo experiences high flows but not the Shire discharging from the Marsh. Although data may be considered reasonable (at best) for most of the record to 1986 when outflows from Lake Malawi were relatively high (and largely unregulated), they are not reliable from the early 1990s, when lake levels were low and outflows became highly regulated (refer to Figure 1.9).

More-recent water-resource studies using Chiromo Station data (*viz*. Atkins, 2011; 2012 and JIKA, 2014) do not mention the hydraulic complexities at this station, although Atkins (2011)[134] does note that flows from 1952 to 1993 appear reasonable, but flows after 1993 appear suspect. The considerable scatter indicated in Figure 3.2, reduced by exclusion of uncertain measurements, is

[133] Atkins (2011) data archive

[134] supporting information in the form of ‘compiled station notes’ (MS Excel file)

attributed to both the downstream influence of the Ruo and to morphological changes.[135] JIKA (2014) describes the river beds at Chiromo[136] as 'stable' - the current study, however, shows this not to be the case. This is dealt with further in this section and in others that follow.[137]

An appreciation of the flow behaviour at Chiromo is found in this station history, circa 1975:
"*The gauging station 1G1 is clearly located in the area of influence of the Ruo River. In extreme cases of very high flows in the Ruo and very low flows in the Shire, reverse slopes may occur for short periods. A unique relationship will exist for the stage/discharge in the channel downstream of the Ruo Tributary, irrespective of the origin of the flow. Under stable or slowly changing flow conditions the water levels at Station 1G1 will equal the water level downstream of the Ruo River confluence plus the hydraulic losses ... Five rating curves were used during period of record [viz. 1953 to 1975].*
With this assumption, stage/discharge curves can be plotted in two[138] ways:

- *Stage at 1G1 against combined Shire (1G1) and Ruo flows;*
- *Stage at 1G1 against Shire flow (1G1);*
- *1G1 for periods when [the] Ruo is [a] negligible contributor ...*

Given sufficient data, a family of curves would emerge ... the interpretation of which would be aided by flow records for the Ruo."

The above discussion highlights the inadequacy of applying (single) rating functions that exclude Ruo flows for transforming measured stage into discharge time-series at the Chiromo Station. Despite this, there is no indication that the suggested approach was pursued, and appreciation of the hydraulic behaviour at 1G1 is not apparent in studies that post-date the NWRP (1986). This, even though since 1986, Shire River flows have been both lower and more-regulated, there has been periodic breaching of the railway embankment and development of a right-bank alternate channel and, in 2015, 'natural'[139] re-routing of the lower Ruo's course.

Prior to the 1990s, the Chiromo station was influenced by the Ruo River's flows. Thereafter, the formation of the Shire's alternate right-bank channel meant that the station, while still influenced by the Ruo's flows, was only monitoring some of the Shire's flows. The 2015 change in the Ruo's course means that presently, some of the combined Shire/Ruo flows route past the gauge, but a substantial proportion flows down the (ungauged) alternate Shire channel.

3.2.2 Ruo River

Given the flow behaviour at Chiromo (discussed in the previous section), it is obvious that flows from the Ruo River cannot be ignored. There are two hydrometric stations of relevance for the lower Ruo, *viz*.: Station 14D1/2 at Sinoya and Station 14D3 at Sandama (refer to Figure 3.1).

[135] It is reasonable to expect that discharge measurements at Chiromo were done at the bridge and exclude the Ruo's flows.
[136] right and left channels; similarly at Chikwawa
[137] Sections 5.4 and 6.2.3.1
[138] three are given
[139] but not disregarding anthropogenic influences through catchment degradation

Table 3.4 Hydrometric record summary for selected stations along the Ruo River

Gauge		Stage		Ratings	
Number	Name	Record length	Missing (%)	Record length	Observations
14D1	Sinoya South	03/11/1980-27/01/1991	15.3	10/08/1979-11/08/1993	48
14D2	Sinoya[140]	03/11/1970-16/07/2002[1]	2.7	-	-
14D3	Sandama	03/11/1980-31/12/2002	10.1	-	0

[1] including limited data 1962/63 - refer to Figure 3.9

The rating data sourced for 14D1 at Sinoya has only a few measurements in the limited range 0.5 to 29 m^3/s. According to the station history (Atkins 2012 data archive), 14D1 and 14D2 are effectively one station, opened in 1953, and of primary status. The cableway at the gauge station was damaged and no high flows were measured after 1970. The archive (hand-drawn graphs) indicates ratings from 1953 for 14D1, with discharges as high as ~500 m^3/s and estimates for discharge during Cyclone Edith (1956) in the order of 5 200 m^3/s. Numerous rating functions[141] developed over the station's history, up to 1987, infer an unstable channel morphology[142] (e.g., deposition of a sand bar (1953); "*Since about 1969 there has been an accelerating rise in the channel bed due to deposition of sand*" (1980); *0 to 2.25-m plates imbedded in silt*" (1983)). Three rating curves were more recently developed based on the 1979 to 1993 ratings for 14D1 (Table 3.4)[143] but clearly with considerable high flow extrapolation.

Station 14D3 at Sandama was established 1979. It is characterised by a "*shifting sandy bed...*", and there have been no discharge measurements at this station (NWRMP, 1986).

Thus, while the overall record lengths (1970 to 2002) from the above hydrometric stations appear promising, there are a great deal of missing data at 14D1/D2; limited and no rating data for 4D1/D2 and 14D3; and sedimentation issues affecting the rating curves at all three stations.

The synthesis of discharge from stage time-series for the Ruo is discussed further in Section 3.4.2.1.

3.2.3 Tributaries of the Shire River between Chikwawa and Chiromo

The records for the hydrometric stations on tributaries of the Shire River between Chikwawa and Chiromo (Table 3.5; also refer to Table 3.1 and Figure 3.1) infers that useful data are available for these stations. Further investigation, however, revealed numerous shortcomings, including: inaccurate discharge time-series and a lack of rating data. For instance: at 1K1 on the Mwanza River, Atkins and Wellfied (2011) note suspect data from 1983; at 1E1 (Mwanphanzi) and 1F1 (Maperera) the same is evident from time-series plots in Figure 3.13 and Figure 3.14, respectively. There is also extensive missing data for 1F2 on the Thangadzi East and a very short record for 1F20 on the Nkhata River.[144] With respect to rating curves, gauged discharges at (E1 and 1F1 are mostly for low flows; and no stage time-series nor rating data could be sourced for the Mwanza Station, which drains the largest[145] catchment area (1 850 km^2) adjacent to the AOI.

[140] also referred to as Sankulani
[141] station history for 14D1 dated 1980 refers to 17 rating functions since 1953
[142] station history notes (Atkins 2012 data archive)
[143] Surface Water Division of the Water Resources Department, MoIWD (2010)
[144] This station was one of a few initially established for *ad-hoc* discharge measurements, but appears to have a short 2-year record from the mid-to-late 2000s.
[145] excluding the Ruo

Table 3.5 Hydrometric record summary for Shire River tributaries between Chikwawa and Chiromo

Gauge		Stage		Ratings	
Number	Name	Record length	Missing	Record length	Observations
1E1	Mwanphanzi	02/11/1970-17/05/2001	13.3	01/11/1981-14/02/2003	159
1F1	Maperera	20/06/1982-31/12/2005	12.2	12/04/1979-22/08/2001	179
1F2	Thangadzi	02/11/1970-21/12/2004	61.9	24/04/1979-10/05/2001	238
1F20	Nkhata	03/05/2006-21/05/2008	2.8	19/11/1981-22/08/2001	164
1K1	Mwanza	01/01/1952-26/02/1997[1]	7.4	-	-

[1] discharge time-series

Thus, measurement-based daily discharge time-series from hydrometric stations on the tributaries were inadequate for direct use in the hydrodynamic modelling, and some means of synthesizing these data for the 11 sub-catchments shown in Figure 3.1, was required. Ideally, this would be done using a (daily) rainfall-runoff model, but this was well beyond scope of this study. Rainfall data were, however, used for runoff estimation.

3.3 Rainfall data

Rainfall data are available from various water-resource studies for the Shire River Basin (e.g., NWRMP, 1986; Kumambala, 2010; WRIS - Atkins and Wellfield, 2011; and JIKA, 2014), but these are mostly monthly data sets, which are not suitable for a hydrodynamic investigation of the Elephant Marsh where flows at (at least) daily time-scales are necessary.

There are two exceptions:

- The Flood Risk Management study of Atkins (2012), which used design hyetographs[146] for various return periods to generate synthetic discharge hydrographs, but these could not be used for this study.
- The JIKA (2014) study, which archived daily (patched) rainfall data for 206 (hydrometric) station locations,[147] for 01/01/1981 to 31/12/2011, which were used for synthesizing the runoff for tributaries of the Shire River described in the next section.

3.4 Analysis and modelling

This section covers the synthesis of daily discharge time-series for the Shire River; for the Ruo River and; for other tributaries between Chikwawa and Chiromo that influence the hydrology of the Marsh.

3.4.1 Shire River

The most critical hydrometric station for this study is 1L12 at Chikwawa, which has a daily stage record from 07/05/1977 to 21/11/2009, with 13.9% missing data (Table 3.3). The quality of this record, together with the computational efficiency for hydrodynamic modelling (Chapter 5), determined the length of record that could be used. In the event, the record was extended/truncated to a 33-year sequence from 01/11/1976 to 31/10/2009. This window covers the period of high outflows from Lake Malawi with little or no flow regulation at the Kamuzu Barrage over the first half of the sequence and a period of considerable regulation starting in the early 1990s (Figure 1.9). Furthermore, apart from

[146] distribution of rainfall over time
[147] identical for many of the stations within the same WRUs

the last six years, the period coincides with data availability for the lower Ruo station at Sinoya (Table 3.4).

For the 33-year period, observed gauge plate recordings were compiled[148] from all available data sources for the hydrometric stations at Liwonde, Matope, Chikwawa and Chiromo. Obvious errors were corrected or excluded from the data-sets.[149] Software was developed that allowed rating functions to be applied on a (hydrological) year-by-year basis to the stage records, to compute discharge time-series. The rating (or stage-discharge) relationships are defined by the power functions:

$$Q = a(z + b)^c$$

Equation 3.1

where Q is discharge (m^3/s), z is stage (or gauge plate level), and a, b and c are coefficients typically determined by regression.

To ensure smooth (discharge) transitions between hydrological years when applying changing rating functions over time, the relationships were weighted according to their temporal position relative to peak flows during successive wet seasons.[150] The parameters of the rating functions (i.e., a, b and c in Equation 3.1) were determined for each station and hydrological year taking into consideration:

- flow continuity along the Shire River, particularly during the dry season and when outflows from Lake Malawi are high compared with tributary contributions;
- the strength of the stage-discharge correlations illustrated in Figure 3.2: well-correlated for Matope, less-so for Liwonde, and substantial scatter displayed for Chikwawa and Chiromo. Thus, the relationship for Matope, determined by regression (based on data from 1978 to 1990), provides a good estimate of Shire River flows during the drier seasons (at least for this period). More substantial temporal changes in the ratings are expected for Liwonde, followed by Chikwawa and Chiromo.

The starting points for the constants in Equation 3.1 were the rating functions fitted by regression to measured data from selected periods. These were (somewhat judiciously) adjusted where measurement-based rating data were missing or where adjustment was needed to preserve flow continuity along the river.[151] Periods of constant functions, indicating stable morphologies (and thus stable rating curves) were obtained for the upper two stations, but downstream, at Chikwawa, the relationships needed adjustment almost annually.[152] The changes in the rating parameters at Chikwawa are in alignment with notes from the station history (refer to Section 3.2.1.3), with a reduction in the '*b*' coefficient representing a change in datum associated with an aggrading bed level as a result of sedimentation.

The hydraulic influence of the Ruo River at Chiromo (discussed previously - refer to Section 3.2.1.4) means that discharge at this location cannot be based on rating functions that are independent of Ruo flows. Historical stage levels at Chiromo are, however, necessary for hydrodynamic model calibration (refer to Section 5.4).

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148 in an MS Excel worksheet
149 records from neighbouring stations provided guidance
150 i.e., the discharges during the wet season are largely determined by the rating function for that hydrological year, but for the dry season are (temporally) weighted using rating relationships from the previous or next year
151 mainly the '*a*' parameter was adjusted
152 The number of different rating relationships applied over the 33-year period at Liwonde, Matope and Chikwawa were 20, 2, and 29, respectively.

Plots of synthesized daily discharge time-series for two 5-year periods, including discharge spot measurements, are illustrated in Figure 3.7. The time-series plot for the period 1981 to 1986 displays suspect discharge measurements[153] at Chikwawa: the maximum lake levels were 476.33, 475.77 and 475.65 m for the three consecutive hydrological years commencing 1982/83; during this period there was no/minimal flow regulation at Kamuzu Barrage; it is therefore inconceivable that the reduction in flow for the 1982/83 year, and increase in discharge for the 1983/84 year (as indicated by the spot measurements), could have occurred between Liwonde and Chikwawa. This illustrates the value of accounting for flow continuity between stations when examining the integrity of rating data, and establishing attendant stage-discharge functions.

For the 33-year period, the discharge time-series at Chikwawa has 15.3% missing daily data, and required infilling (or patching), which was done as follows:

- Tributary contributions between Liwonde and Matope were estimated using levels from hydrometric stations[154] in the upper Shire Catchment, and computing the coefficients in Equation 3.1, wherein the flow is the catchment[155] discharge. Coefficients were determined by regression using daily discharges at Liwonde and Matope (discussed previously) and station levels. Since level data are not available for all stations covering the 33-year period, regression values were computed for different combinations of available station data. A time-series was thus synthesized for Matope, based on upstream Shire River discharges at Liwonde, and estimates of intervening tributary inflows. This was used to infill missing daily data at Matope.
- The same procedure[156] was followed between Matope and Chikwawa to produce a patched daily time-series at Chikwawa, which is the upper boundary in the hydrodynamic model presented in Chapter 5.

Figure 3.8 presents plots of the daily discharge time-series for the Shire River at Liwonde, Matope and Chikwawa for the 33-year period 1976 to 2009.

3.4.2 The Ruo River and other tributaries of the Shire River between Chikwawa and Chiromo

3.4.2.1 Ruo River

In Section 3.2.2, reference was made to historically observed deposits at the hydrometric stations, which suggest sedimentation of the lower Ruo River. This suggestion is supported by daily gauge levels recorded at Sinoya (Station 14D2; plotted in Figure 3.9 for the period 1962 to 2004). The measured levels have systematically increased by ~6.4 m over the 42-year record, at an average rate of 0.14 m/yr. The overall trend appears to be slightly lower for the first half of the period, increasing thereafter (0.11 and 0.19 m/yr before and after 1980, respectively). Extrapolating the initial rate of aggradation back to 1953 when the station was established, gives a zero datum that seems reasonable,[157] and provides an overall increase of 7.4 m over half a century, which is substantial.[158] Since there are

[153] indicated by lightly-shaded markers in Figure 3.2

[154] namely, 1R3 on the Rivi Rivi River and 1C9 on the Lunzu River. Although the Lunzu River Catchment is downstream of Matope, this station has a reasonable historical record, and was used to represent left bank inflows between Liwonde and Matope (no other station exists)

[155] i.e., not hydrometric 'station'

[156] The primary hydrometric stations used were 1C9 on the Lunzu River and 1M1 on the Nkurumadzi River. No level data was sourced for the Lisungwe River, and those from 1R3 on the Rivi Rivi River were used where necessary.

[157] as it would have been located as close to the lowest water or bed level as possible

[158] *viz*. two-and-a half stories

insufficient rating data to characterise temporal changes in stage-discharge (and express observed stage as measurement-based discharge), use of this water level information required an alternative approach:

- for the period of modelling (1976 to 2009), the incomplete gauge level time-series for Sinoya (Figure 3.9) was infilled using relative observations from Sandama (14D3) as well as the hydrometric station at Road Bridge (14C2) located in the upstream catchment;
- this time-series was detrended on an annual basis using a linear datum adjustment between the lowest levels in successive years.[159]

The stage time-series was transformed to discharge time-series using a single set of coefficients[160] in the rating function (*viz*. Equation 3.1) for the period 1976 to 2004.[161] The coefficient values were determined as part of the hydrodynamic modelling (refer to Section 5.4.1) using observed stage levels at Chiromo, concentrating on periods when the Shire River experienced steady flows and hence fluctuations were largely a result of backup due to fluctuating flows in the Ruo River.

The resultant discharge time-series is plotted in Figure 3.10 for an 11-year period from 1980, for which data are also available for Station 14D1 from the HYDSTRA database. The plots agree well for the first half of the sequence, but thereafter the HYDSTRA dataset appears to increasingly overestimate particularly high flows. This is attributed to inaccurate rating of the station; for the reasons discussed previously (Section 3.2.2).

The time-series for the Ruo falls five years short of the required sequence for the Shire (derived from Chikwawa) which extends to 2009, so some means of further extending the dataset was necessary. This was done by making use of the Antecedent Precipitation Index (API), with daily rainfall data available from the JIKA (2014) study archive (refer to Section 3.3). The API is an exponential two-parameter decay function of precipitation that reflects the rate of soil moisture depletion (e.g., Hughes and Slaughter, 2015):

$$API_i = {API_{i-1}}^k + P_i$$
$$If\ P_i < P_t\ then\ API_i = {API_{i-1}}^k$$

Equation 3.2

where *i* is the daily time step, *k* is the decay, P_i is precipitation on day *i*, and P_t is the threshold value. A modification of the threshold precipitation was applied, using an excess value (P_e):

$$API_i = {API_{i-1}}^k + P_e$$
$$If\ P_t \geq API_{i-1}\ then\ P_e = P_i - (P_t - API_{i-1})\ with\ P_e \geq 0, else\ P_e = P_i$$

Equation 3.3

[159] minima were located within calendar years; an initial detrending was carried out prior to stage infilling, thereafter reapplied to the stage-patched time-series
[160] given by *a* = 109, *b* = 0.09 and *c* = 1.46
[161] Stage records for Sandama only extend to 2002 and for Road Bridge to 2008 but with large gaps after 2004.

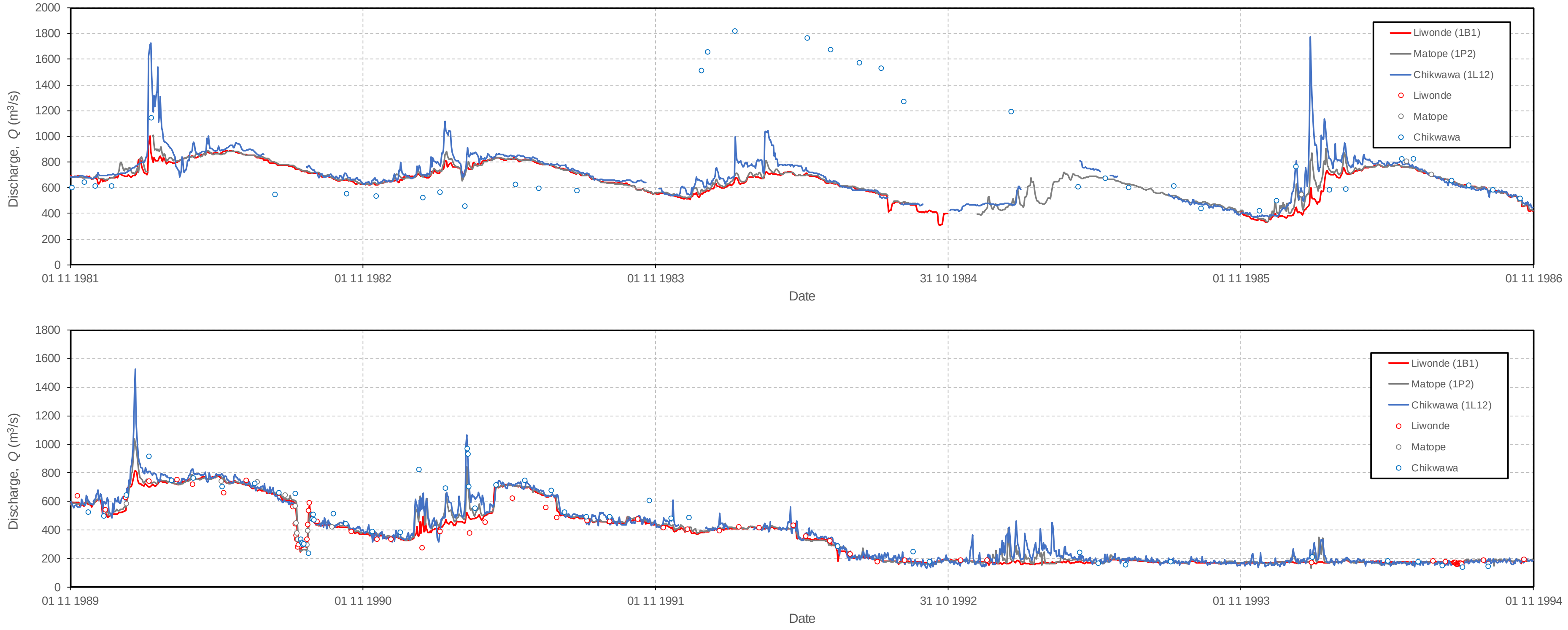

Figure 3.7 **Synthesized (unpatched) daily discharge time-series for the stations at Liwonde (red), Matope (black) and Chikwawa (blue) for two selected 5-year periods, applying time-dependent rating functions. The circular markers are discharge spot measurements, constituting the rating data plotted in Figure 3.2**

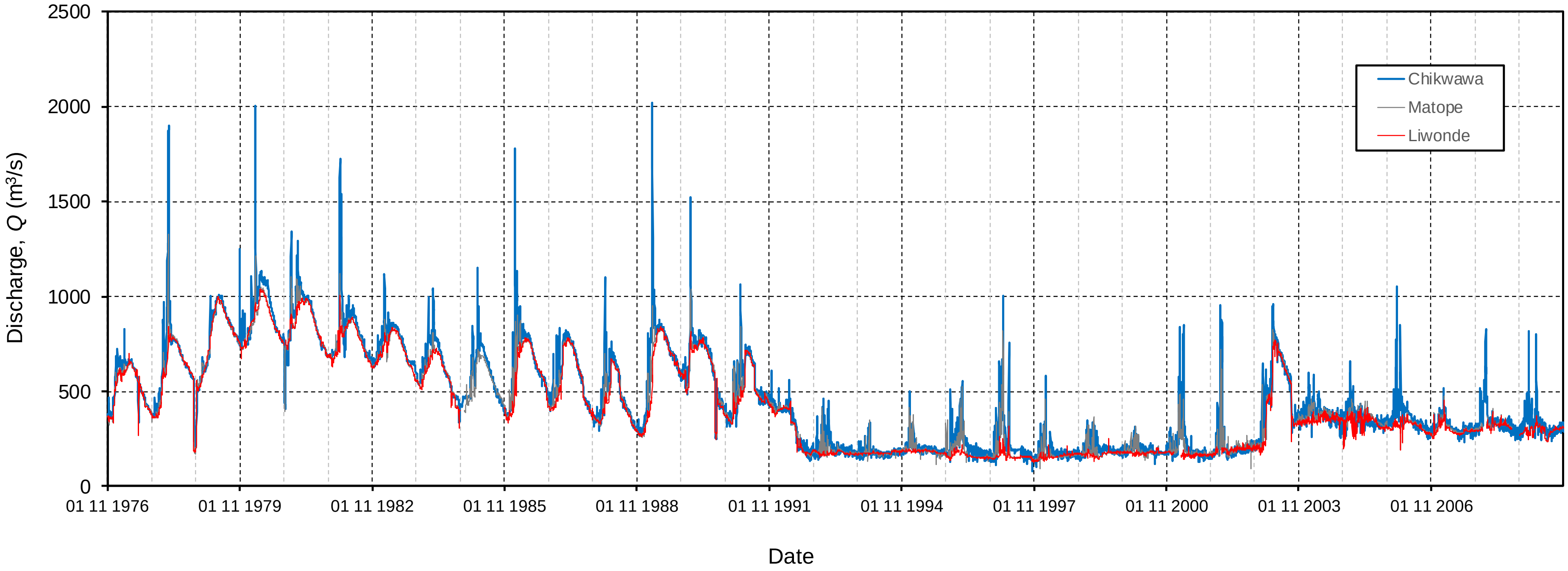

Figure 3.8 **Daily discharge time-series for the hydrometric stations at Liwonde (unpatched), Matope and Chikwawa (patched) for the 33-year period 1976 to 2009**

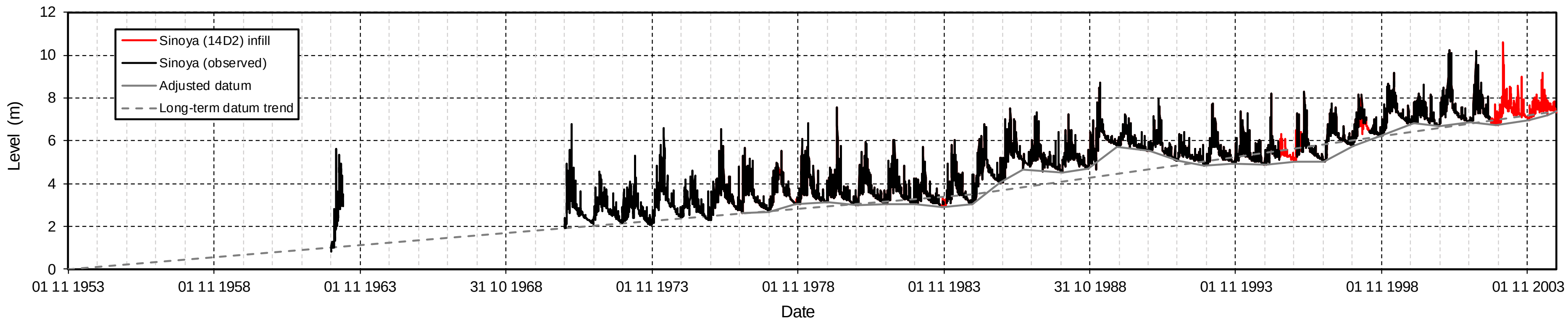

Figure 3.9 Gauge level time-series from 1962 to 2004 at the Sinoya (14D2) hydrometric station on the lower Ruo River (refer to Figure 3.1)

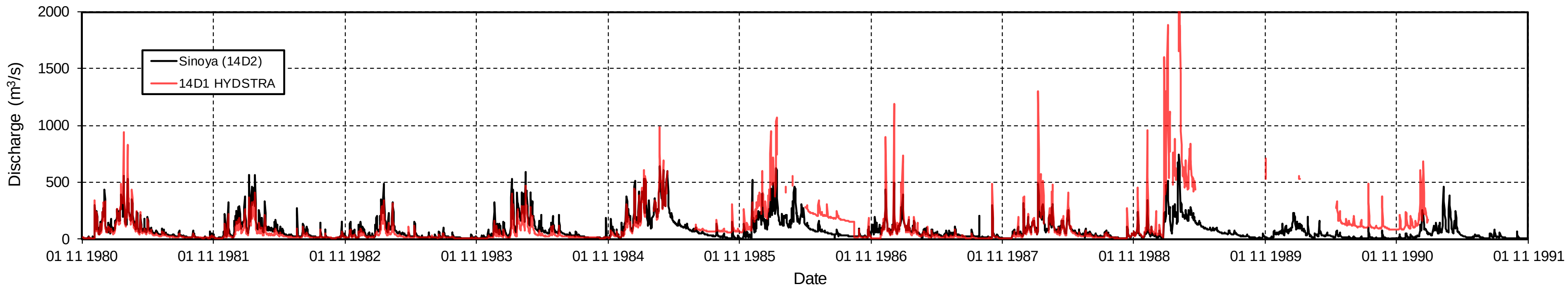

Figure 3.10 Modelled discharge time-series from 1980 to 1991 at the Sinoya hydrometric station on the lower Ruo River, also showing the comparative plot for 14D1 extracted from HYDSTRA

Equation 3.3 was used to compute a daily API time-series, which was expressed as an exceedance relationship (Figure 3.11). This, when used in conjunction with the corresponding discharge-exceedance relationship (for equivalent percentage points), facilitated infilling or extending of discharge time-series.[162] The parameter values of the decay (*k*) and threshold precipitation (P_t) were determined by obtaining suitable agreement between API-derived and typically measurement-based[163] discharge time-series. For the Ruo at Sinoya, the parameters used were k = 0.985 and P_t = 0 mm, with rainfall aggregated for four Ruo sub-catchments (refer to Figure 3.1). Figure 3.12 is a comparative plot of discharge time-series derived from stage time-series[164] and using the API/discharge-exceedance approach described above. The estimates agree satisfactorily, although missing events not captured in the rainfall data are evident, as are different rates of hydrograph recession during the late 1990s. The latter appears to be related to detrending analysis, since years displaying differences in recession correspond with periods of higher relative sedimentation and consequent datum-shift (refer to Figure 3.9). Using the API-derived discharges, the stage-derived time-series was extended to 2009, thus producing a synthesized daily record for the 33-year period as for the Shire River at Chiwawa. For this period, the modelled Mean Annual Runoff (MAR) is 76 m^3/s. Comparative values from other studies vary considerably: 49 (JIKA, 2014); 53 (Niras/DHI, in prep.), 60 (NWRMP, 1986), 88 (Kumambala, 2010), and 109 (Atkins and Wellfied, 2011).[165] The MAR from this study appears to be in the right range, and importantly, the approach provided an estimate of daily flows which are not available from any of the other water-resource directed studies.

3.4.2.2 Other tributaries

In Section 3.2.3, the inadequacy of discharge records from the hydrometric network on the tributaries between Chikwawa and Chiromo was discussed, highlighting the need for an alternative method for synthesizing time-series data. The API/discharge-exceedance approach used for extending the Ruo River's record was applied for the 12 sub-catchments, with additional assumptions, since for most of the tributaries discharge-exceedance data are not available as they are ungauged, or records are inadequate (*viz*. 1E1 on the Maperera, and 1F2 on the Thangadzi East); only the record for the Mwanza (station 1K1) was directly used.

The discharge-exceedance relationship for the Mwanza (Station 1K1, refer to Figure 3.11) was based on the HYDSTRA records for the 36-year period 1952 to 1988,[166] and for the API time-series, parameters values in Equation 3.3 were k = 0.970 and P_t = 20 mm. The synthesized daily time-series comprises HYDSTRA records for the period 1976 to 1980, and thereafter to 2009, from the API/discharge-exceedance approach.

[162] Software was coded for this purpose.
[163] 'Measurement-based', analyses also required, *viz*. detrending and stage-discharge rating
[164] Refer to Footnote 160
[165] Data periods were 5-year, i.e., extremely limited (JIKA, 2014); 1976 to 2009 (Niras/DHI, in prep.); 1981 to 1990 (Kumambala, 2010); and 1987 to 1990, i.e., extremely limited (Atkins and Wellfield, 2011). The NWRMP (1986) value excludes the Mozambican portion of the catchment.
[166] Source: MoIWD; 5.8% data missing for this period

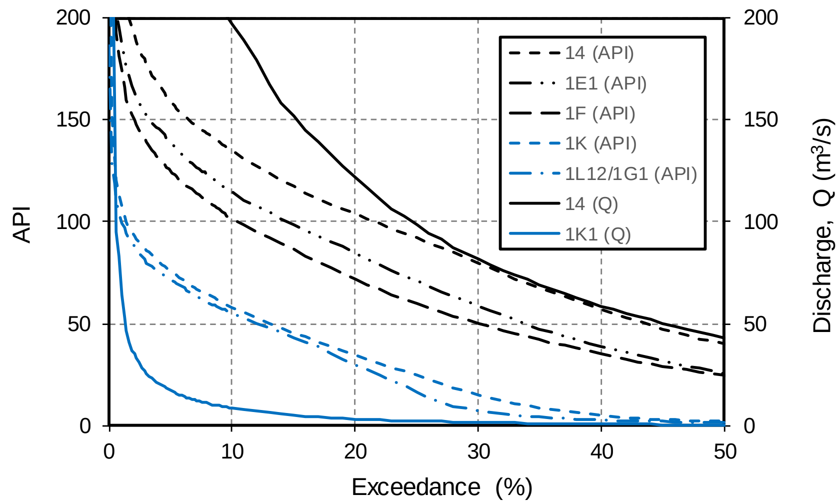

Figure 3.11 API- and discharge-exceedance relationships for Shire sub-catchments, and hydrometric stations, respectively

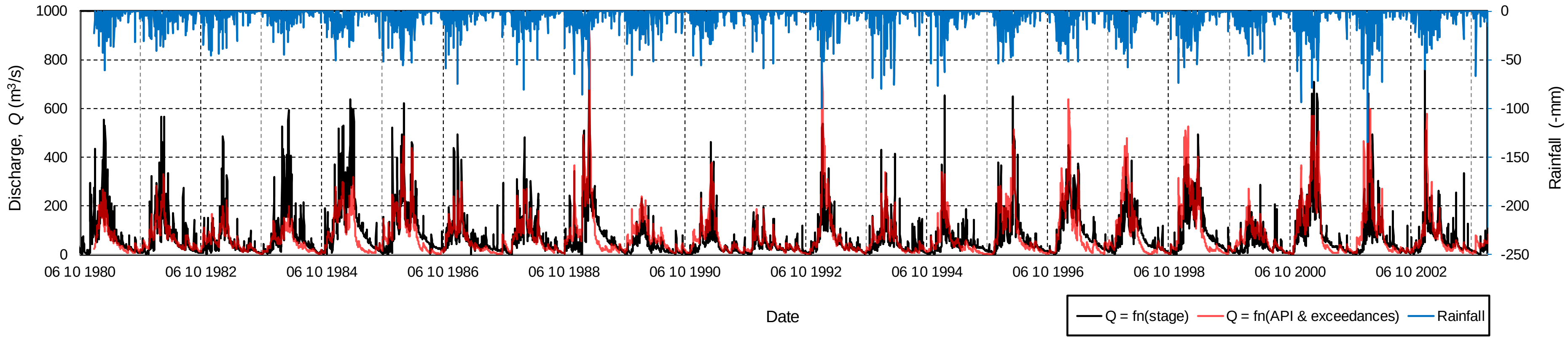

Figure 3.12 Modelled discharge time-series from 1990 to 2004 at the Sinoya hydrometric station on the lower Ruo River, with discharges derived from stage (refer to Figure 3.9) and API time-series combined with API/discharge-exceedance relationships; daily rainfall is also indicated ('Q' is discharge, 'fn' denotes 'a function of')

For the remaining 11 sub-catchments (*viz*. 1E2, 1F1-3, 1H1-5 and 1G, 1L) daily rainfall estimates[167] for the period 1981 to 2010 from the JIKA (2014) archive have been applied. Unfortunately, no data (rainfall or suitable discharge) could be sourced pre-01/1981, and tributary flows (excluding the Mwanza which is the largest of the sub-catchments) are ignored for this 4-year period. Serendipitously, this coincides with a period of high flows in the Shire River (refer to Figure 3.8) with minimum wet-season discharges in the range 600 (1976/77) to 1000 m^3/s (1979/80), and the relative contributions of these largely non-perennial tributaries would be small. Given, however, that no or inadequate discharge records are available for these smaller tributary catchments, it has been necessary to use discharge-exceedance relationships from local 'reference' catchments.[168] This approximation reduces runoff by relative catchment area, but also applies a less obvious adjustment, where discharge is also factored by relative API.[169]

To provide indications of the relative accuracy of the synthesized daily discharge time-series for the tributaries, comparative plots, which include hydrometric (HYDSTRA) records and rating observations (where available) are provided in Figure 3.13 to Figure 3.16 for selected periods at hydrometric stations. These include Station 1E1 on the Mwanphanzi River, 1F1 on the Maperera River, 1F2 on the Thangadzi East River, and 1K1 on the Mwanza River, respectively:

- for the Mwanphanzi River, the synthesized time-series compares reasonably well with rating and hydrometric data up to 1991, thereafter the HYDSTRA records are incomplete and clearly erroneous; the highest spot discharge measurement over the period 1981 to 2003 is only 13.9 m^3/s;[170]
- for the Maperera River, excluding periods in 1991 and 1996, the synthesized and hydrometric estimates compare adequately, with both, however, giving higher estimates for the wet season than indicated by rating measurements - this is surprising, as the rating data would ostensibly have been used to compile the hydrometric records; the maximum measured spot discharge over the period 1979 to 2001 is only 5.4 m^3/s;[171]
- although the Thangadazi East at Gooke (1F2) is a small proportion of sub-catchment 1F3 (~10%), and only 0.6% of the reference (Ruo) catchment's area, it is encouraging to note that synthesized discharges are in the appropriate range based on measurement-based records; inaccurate hydrometric records appear to occur between 1994 and 1998; synthesized hydrograph recession could potentially be improved[172] with further analyses;
- for the Mwanza at Tomali (1K1), the synthesized and hydrometric records compare satisfactorily overall - better for some years than others; discrepancies are largely attributed to inaccurate hydrometric data and/or rating functions, but not excluding inadequate rainfall data and the simple modelling approach based on an antecedent precipitation index (*viz*. Equation 3.3).

[167] direct (i.e., for the relevant sub-catchment), or using adjacent catchments
[168] The Ruo for sub-catchments 1E2 and 1F1-3, and the Mwanza for 1H1-5, 1G and 1L
[169] The need for this additional adjustment is evident from the following explanation: for a sub-catchment of identical size and rainfall-runoff characteristics to the reference catchment, but of lower rainfall (of similar temporal distribution) than the reference catchment, the runoff would accordingly be lower. For a given day, however, the exceedance (from the API time-series, combined with the API-exceedance relationship) should be very similar to the reference, resulting in similar flow for the sub- and reference catchment. This is a consequence of the API being directly linked to discharge through exceedance values. Thus, it is necessary to adjust the reference discharge, and this was done with the ratio of sub-to-reference catchment API, using the reference's API corresponding to the relevant (i.e., sub-catchment's daily) exceedance value.
[170] source: data archive, MoIWD
[171] source: data archive, MoIWD
[172] i.e., the decay (*k*) parameter in Equation 3.3

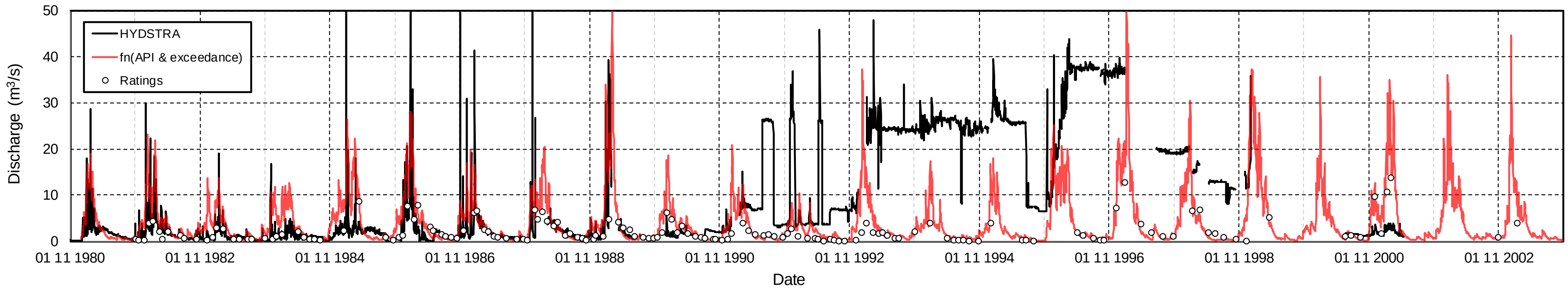

Figure 3.13 **Measurement-based (HYDSTRA) and synthesized (API-derived) discharge time-series from 1980 to 2003 at the hydrometric station on the Mwanphanzi River at Pokonyola (1E1), showing spot rating measurements**

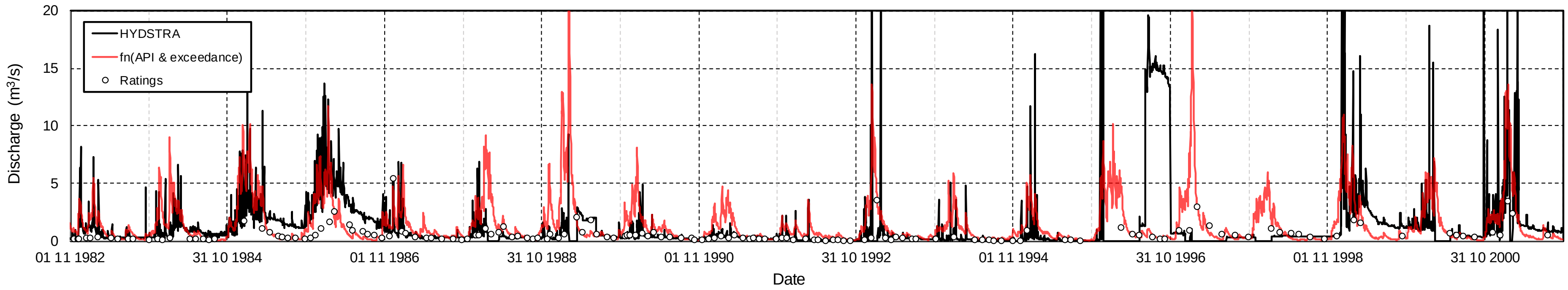

Figure 3.14 **Measurement-based (HYDSTRA) and synthesized (API-derived) discharge time-series from 1982 to 2001 at the hydrometric station on the Maperera River at Mfumbi (1F1), showing spot rating measurements**

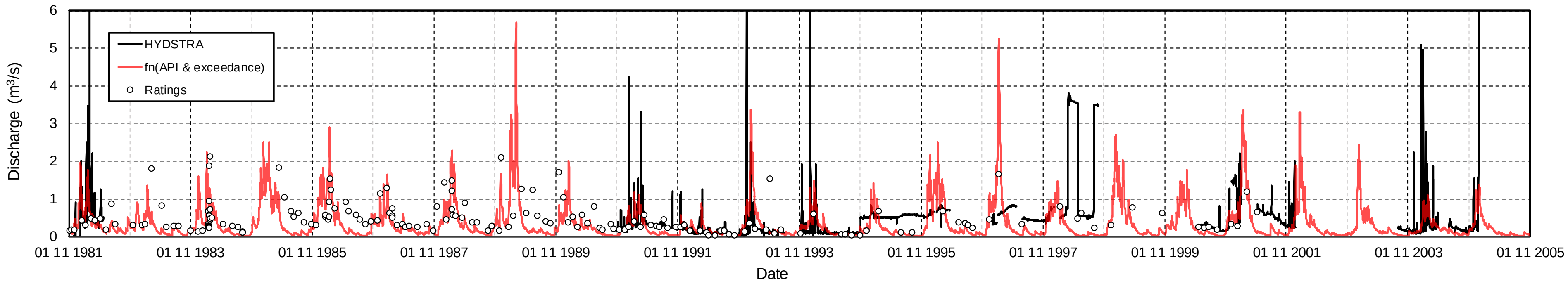

Figure 3.15 **Measurement-based (HYDSTRA) and synthesized (API-derived) discharge time-series from 1981 to 2005 at the hydrometric station on the Thangadzi East at Gooke (1F2)**

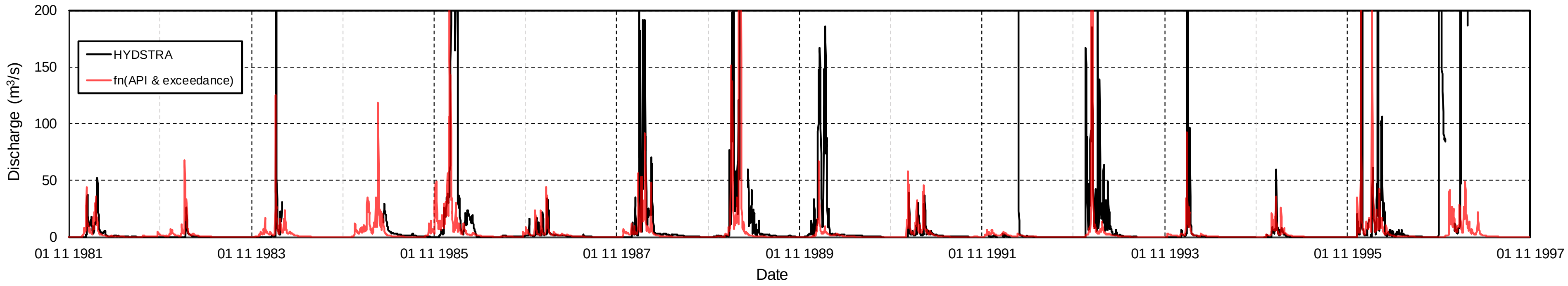

Figure 3.16 **Measurement-based (HYDSTRA) and synthesized (API/discharge-exceedance approach) discharge time-series from 1981 to 1997 at the hydrometric station on the Mwanza River at Tomali (1K1)**

In the interests of developing a hydrodynamic model for the Marsh (Chapter 5), the synthesized runoffs from the tributary catchments (between Chikwawa and Chiromo) are considered realistic, and certainly adequate. It is pertinent to contextualise this sufficiency within the reasonable expectation for this study[173] - this being that historical records from the national gauging network be used, with no need for in-depth data collation, review and analyses of hydrological information.

The final discussion in this hydrological chapter deals with climate change, which is central to the broader Elephant Marsh study.

3.5 Climate change

Climate change is a focus this study. It is broadly defined '*as a change in the statistical distribution of weather patterns, when that change lasts for an extended period (decades to millions of years)*'.[174] It may refer to a change in average weather conditions, or to temporal changes around longer-term average conditions (e.g., frequency of extreme weather events). Climate change is caused by natural factors (e.g., biotic processes, variations in solar radiation), but certain human activities[175] have also been identified as substantial causes of more-recent change, i.e., since the mid-to-late 20th century. The latter is often referred to as 'global warming' or 'global climate change'. This definition is consistent with the Intergovernmental Panel on Climate Change (IPCC), which views climate change over the longer-term (i.e., decades or more), whether due to natural or anthropogenic influences. However, the term 'climate change' is also often used to refer entirely to more-recent human-induced effects (e.g., the United Nations Framework Convention on Climate Change (UNFCCC)).

As noted previously (Section 2.5), long-term climatic information spanning some 1 200 years is available for consideration in this study. This has the advantage that it extends well beyond more-recent times associated with carbon emissions due to human activities, and that it provides a better picture of long-term cyclical patterns in the region's climate.

The hydrodynamic analysis (Chapter 5) and DRIFT sub-study (Brown *et al.* 2016), however, use hydrological time-series spanning a recent period (*viz.* 1976 to 2009). This is largely because there are no flow records for a longer period. Thus, the 'climate-change' scenarios evaluated in these modelling exercises include aspects of climatic futures 'superimposed' on a historic climatic regime (i.e., incorporating natural change over a short 33-year period), which while extremely useful are limited because they exclude the long-term, i.e., longer than 33 years, cyclical patterns in the region's climate.

Thus, to fully understand the future of the Marsh, it is necessary to contextualise the anthropogenically-induced climate change projections within the broader longer-term natural climate change.

3.5.1 Recent climatic trends and future projections

Simulations with Global Circulation Models (GCMs) for the 21st century predict precipitation increases in high latitudes and parts of the tropics, and decreases in some subtropical and lower mid-latitude regions (IPCC, 2008). Outside of these areas, however, the direction and magnitude of projected changes varies between models, leading to substantial uncertainty. Generally, annual average river flow and water availability are predicted to increase at high latitudes and in some tropical areas, and decrease over some dry regions at mid-latitudes and in the dry tropics. Many semi-arid and arid areas

[173] as outlined in the Inception Report
[174] https://en.wikipedia.org/wiki/Climate_change
[175] resulting in the increased levels of atmospheric carbon dioxide produced by fossil fuels

(e.g., southern Africa) are particularly vulnerable to the impacts of (anthropogenic) climate change projections, and are expected to experience a decrease in water resources - this being expressed with high confidence (IPCC, 2008). Increased precipitation intensity and variability projections are that the risks of flooding and drought will increase in many areas. The frequency of heavy precipitation events (or proportion of total rainfall resulting from heavy falls) will very likely increase over most areas during the 21st century, with concomitant consequences for flooding. Simultaneously, the proportion of land surface in extreme drought is likely to increase, in addition to a tendency for drying in continental interiors during summer, especially in the sub-tropics, low and mid-latitudes.[176]

While central to the broader 'climate resilient livelihoods' study, the direct relevance of climate change to this (hydromorphological) component concerns:

- scenario (hydrodynamic) modelling of possible future management strategies that include (anthropogenic) climatic and associated hydrological effects, and;
- provision of historical information that can be used to develop a conceptual understanding of past (longer-term) trends in the Marsh's hydromorphological functioning and, based on this understanding, predict its future resilience.

The first of these requires the synthesis of modified daily discharge time-series, relative to a 'baseline' condition,[177] that reflects changes in runoff due to possible climate change futures. Since it was never intended that detailed hydrological modelling be done in this study, attention was first directed to completed/concurrent projects under the auspices of the SRBMP, or elsewhere, where the effect of climate change on current and future water-resource developments has been/is being addressed. This was provided through the thematic study of Van der Weerts and Wright (2015) of 'climate change analysis' - which is a component of the (Niras/DHI) 'Development of a Basin Planning Framework' Project.[178]

Van der Weerts and Wright (2015) made use of 'Climate Wizard',[179] which incorporates different GCMs to assess changes in rainfall, evaporation and minimum and maximum temperatures. Ensemble analyses[180] using different GCM predictions were carried out to compute hydrological changes for three climatic futures that relate to low (B1), moderate (A1B) and high (A2) carbon emission scenarios.

- The moderate (A1) condition assumes a world of very rapid economic growth with a global population peaking mid-21st century and rapid introduction of new/more efficient technologies - A1B represents a balance between fossil and alternative energy sources;
- B1 describes a convergent world with the same global population as A1, but with more rapid changes in economic structures towards service and information economies;
- A2 describes a very heterogeneous world with high population growth, slow economic development and technological change.

As mentioned previously, these climatic futures only consider changes in carbon emissions resulting from (recent) anthropogenic activities.

The results or Van der Weerts and Wright's (2015) analysis are presented for two time periods: 2046 to 2065, and 2081 to 2100 (i.e., mid- and end century, respectively). In them, the yield of Lake Malawi shows increases but with considerable variation for the different scenarios: 6 to 23% at mid-century, and 15 to 46% at 2100. For the Shire Basin,[181] a slight increase in runoff was predicted for Scenario A2.

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176 Malawi lies in the low-latitudes
177 discussed further in Section 5.5.1
178 SRBMP sub-component A1
179 http://www.climatewizard.org/index.html
180 combining the results
181 downstream of Lake Malawi

The other two scenarios indicated decreases in the range 6 to 9%. Monthly discharge time-series for each WRU downstream of Lake Malawi for the period 1960 to 2009 were computed.

Hydrological time-series (monthly) for various water development scenarios within the Shire Basin, that incorporate these climatic futures, were obtained from the Basin Planning Framework Project, for use in the hydrodynamic modelling of the Elephant Marsh. Other than being convenient, it has contributed to project integration within the SRBMP, facilitating the interpretation of cross-project results. Challenges, however, included the different time-scales (monthly versus daily), and the need for similar, or at least comparative, baseline conditions used in the different studies. These are addressed further in the scenario modelling section (5.5.1) of Chapter 5.

Based on predicted temperature increases for the mid- and end century, Van der Weerts and Wright (2015) predicted average increases in annual maximum 5-day precipitation in the range 10 to 12%, and 12 to 23%, respectively. For the dry seasons, less rainfall is predicted, coupled with average increases in the length[182] of these seasons, by 13 to 18% at mid-century and 15 to 23% at 2100.

It is informative to compare the results of the Van der Weerts and Wright (2015) analysis, which was directed specifically at Lake Malawi and the Shire Basin, with other country-wide projections. McSweeney *et al.* (2012) included the following projections for precipitation within the United Nations Development Programme (UNDP) climate change profile for Malawi:

- "*Recent climatic trends:*
    - *year-to-year variability in rainfall is very strong and this can make it difficult to identify long term trends, but nonetheless rainfall observations do not show statistically significant trends;*
    - *there are no statistically significant trends in the extremes indices calculated using daily precipitation observations.*
- *CGM projections of future climate:*
    - *projections of mean rainfall do not indicate substantial changes in annual rainfall. The range of projections from different models is large and straddles both negative and positive changes in the range -13 to 32%. Seasonally, the projections tend towards decreases in dry season rainfall (July to November), and increases in wet season rainfall (December to May);*
    - *overall, the models consistently project increases in the proportion of rainfall that falls in heavy events (in the annual average) under the higher emissions scenarios (A2 and A1B), of up to 19% by the 2090s. These increases mainly arise from increases in heavy events in the wet seasons (December to May), and are partially offset by decreases in June to November;*
    - *the models consistently project increases in 1- and 5-day rainfall maxima by the 2090s under the higher emissions scenarios: of up to 26 mm in 1-day events, and 39 mm in 5-day events. These also generally increase in December to May, but decrease in June to November*."

Concerning other regional climate change information, the authors note that "*Model simulations show wide disagreements in projected changes in the amplitude of future El Niño Southern Oscillation (ENSO) events. Since Malawi's climate can be strongly influenced by ENSO, this contributes to uncertainty in climate projections for this region*."

An 'analysis of existing weather and climate information for Malawi', by Vincent *et al.* (2014), includes the following recent climatic trends, and future projections:

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[182] expressed as increases in consecutive dry days

- "*Recent climatic trends:*
    - *long term trends in* [observed] *precipitation are more difficult to discern (than temperature), given the nature of the underlying variability (Simelton et al., 2013). Observations of rainfall over Malawi do not show statistically significant trends either in terms of total amount, the date of rainfall onset, or the length of the wet season.*
- *Future climate projections from GCMs:*[183] *some models project Malawi will become drier in the summer, and others, wetter - but uncertainties are emphasized by differences being mostly less than one standard deviation from current variability. In terms of winter rainfall there is generally a drying trend.*
- *Future regional climate projections from statistical downscaling:*[184]
    - *although increased mean annual maximum temperatures are predicted, it is also important for natural resource-based livelihoods (and their effects on land and resource management) to assess how those changes will manifest themselves on a seasonal basis. The season with the greatest increase in temperature will be September to November (i.e., early summer). This has implications, since it is the traditional planting season in Malawi.*
    - *downscalings are based on GCMs, and since the latter have considerable variation in rainfall, results should be interpreted as the direction rather than the extent of change - an increase in rainfall is predicted for Malawi. Whilst models do not agree on whether there will be an increase or decrease in winter and during early summer, they do predict an increase in rainfall in the second part of summer (January to March), and March to May.*
- *Future regional climate projections based on dynamical downscaling:*[185] *again, some models project an increase, and others a decrease, in annual rainfall. There is a high level of agreement with statistical downscaling: although there is uncertainty about winter rainfall, the second part of summer and March to May will likely receive increases in rainfall. Whilst the statistical downscaling of the models is inconclusive for early summer, dynamical downscaling shows a definite decrease in rainfall in the early part of summer (September to November), i.e. the traditional planting time*."

Thus, recent climatic trends and future projections can be summarised as follows:

- McSweeney *et al*., 2013: inter-annual rainfall variability is high, making it difficult to distinguish long-term tendencies, but nonetheless observations over Malawi do not show statistically significant trends; there are also no statistically significant trends in the extremes indices[186] calculated using daily precipitation observations.
- The range of projections in mean annual rainfall from different models is large, and includes both decreases and increases:
    - Van der Weerts and Wright, 2015: for three climatic futures analysed, the yield of Lake Malawi increases by 6 to 23% at mid-century, and 15 to 46% at 2100. For the Shire Basin downstream of Lake Malawi, runoff predictions give both marginal increases and reductions of up to 9%;

[183] source: IPCC, 2013
[184] source: Davis, 2011; downscaling is the general name for a procedure to take information known at large scales to make predictions at local scales. The two main approaches to downscaling climate information are dynamical and statistical. Dynamical downscaling requires running high-resolution climate models on a regional sub-domain, using observational data or lower-resolution climate model output as a boundary condition. These models use physical principles to reproduce local climates, but are computationally intensive. Statistical downscaling is a two-step process consisting of i) the development of statistical relationships between local climate variables (e.g., surface air temperature and precipitation) and large-scale predictors (e.g., pressure fields), and ii) the application of such relationships to the output of global climate model experiments to simulate local climate characteristics in the future (https://gisclimatechange.ucar.edu/question/63)
[185] source: Davis, 2011
[186] quantitative measures of extreme climatic conditions

  - McSweeney *et al.,* 2012: projected mean annual rainfall for Malawi is in the range -13 to +32%.
- Seasonally, the GCM projections tend towards decreases in dry season rainfall (July to November) while downscaling projections are uncertain. Predictions are for increases in wet season rainfall (December to May), with downscaling (Vincent el al., 2014) indicating the second half of summer (March to May) which may be offset, however, by drier early summers (dynamical downscaling).
- The models consistently project increases in the proportion of rainfall falling in heavy events during the wet seasons, under the higher emissions scenarios.

It is interesting that McSweeney *et al.* (2012) note "*no statistically significant trends in the extremes indices calculated using daily precipitation observations*". This seems to contradict reports of increased frequency of floods and droughts in recent times (e.g., ActionAid, 2006; UNDP, 2007/8 and Kumambala, 2010). From a graphic published in ActionAid (2006), reproduced in Figure 3.17, Malawi experienced 27 droughts and floods over the period 1970 to 2006, of which 22 occurred since 1990. A UNDP (2007/8) report and Kumambala (2010) provide further comment on this graphic[187] and other climate disasters, noting "*that droughts and floods have increased in frequency, intensity and magnitude over the recent decades and have adversely impacted on food and water security, water quality, energy and the sustainable livelihoods of rural communities*." The UNDP (2007/8) report describes a decreasing (linear) trend in mean seasonal rainfall for Karonga for the period 1900 to 2005, but which does not appear obvious given the high inter-annual variability.

Although McSweeney *et al.* (2012) noted no statistical significance in the extreme indices from precipitation observations (i.e., historically), climate change models project increases in the proportion of high intensity rainfall events; a tendency towards decreases in dry season rainfall and concomitant increase in dry season longevity; and potentially drier early summers. Some reports (e.g., USAID, undated) also state that "*climate variability and change are already affecting Malawi, which has experienced a greater incidence of dry spells and intense rainfall events over the last two decades".* Certainly, Figure 3.17 indicates increased occurrence of flooding; but not necessarily droughts.

[187] Kumambala (2010) references the graphic to the Malawi National Statistics Office (NSO), 2006 (htttp://www.nsomalawi.mw), but this could not be sourced. Consequently, the basis for defining the incidence of droughts and floods is unknown. It would appear, however, that droughts are defined on an annually, whereas multiple floods may occur within a hydrological year (e.g., nine floods in the period 2000 to 2006).

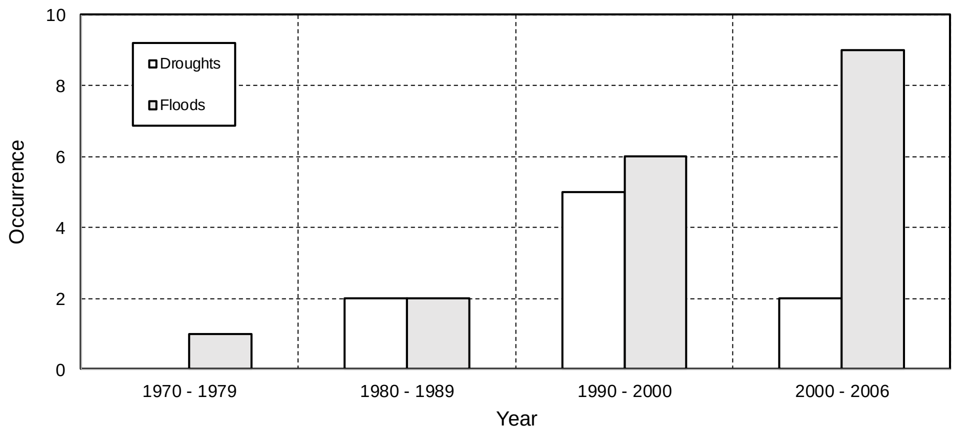

Figure 3.17 Incidence of droughts and floods in Malawi between 1970 and 2006, after ActionAid (2006)

It is possible that the observed increased incidences of droughts and floods are a result of factors other than climate change:

- Changes in landcover, specifically deforestation and removal of indigenous vegetation (Section 6.1), will lead to:
  - more rapid response of runoff, thus exacerbating flooding, and;
  - increased sedimentation of river channels, which results in reduced conveyance and a tendency for increased inundation/flooding of adjacent areas.
- In the 1990s and 2000s outflows from Lake Malawi (and hence flows in the Shire) were considerably lower than those in preceding years (1970s/1980s; Figure 3.8). Thus, in the 1990s and 2000s the wetlands and floodplains along the lower Shire Valley (Elephant Marsh, Ndinde wetlands, etc.), always highly valued for farming activities (and related habitation) given the fertile lands and proximity to water, would have been more accessible, and by inference more populated, than in the earlier period (particularly given the drought conditions of the early 1990s). The consequence is that, post 1990, high flows would have affected more people and more livelihoods, which could lead to the perception[188] of increased flooding frequency.
- The Bangula-Chiromo railway embankment has a damming-effect during floods resulting in increased inundation of the (upstream) Marsh, and attenuated downstream floods resulting from Shire River flows.[189] The embankment was breached between 1989 and 1997,[190] with the subsequent formation (and progressive erosion) of an alternate channel to the 'historical' one that passes under the Chiromo Bridge (refer to Figure 2.11 and Figure 2.13). This breaching would have acted to reduce upstream inundation and increase downstream flooding, the extent of which is unknown.

There are many records of extreme floods prior to 1970, with three occurring between 1948 and 1956: in 1948 Chiromo Bridge was washed away (Section 2.3); there was extensive flooding in February 1952 (Figure 2.10) and; extensive flooding 1956 associated with Cyclone Edith. It is thus debatable if the perceived increase in flooding over more-recent decades is a result of climate change, a result of other contributing factors, or a combination of the two. There does, however, seem to be consensus that into the 21st century (anthropogenically-induced) climate change will result in an increase in both

[188] As mentioned previously, the rationale for defining flooding incidents is unknown.
[189] as opposed to Ruo River flows
[190] There is uncertainty regarding the date (refer to Section 2.3), although it may have occurred progressively over a period.

floods and droughts. In the Shire Valley, the most-recent example of this variability is the ‘failed’ wet season of 2015/16, which followed the devastating floods of January 2015 (Figure 2.11).

This increased frequency and magnitude of extreme weather events, coupled with a low adaptive capacity, has resulted in Malawi being considered as one of the vulnerable African countries to the negative impacts of global climate change (Kaunda and Mtalo, 2013). Within Malawi, the country’s most susceptible regions include the Shire Valley (National Programmes of Actions[191]); where 98% of grid-based electricity is generated and where the Elephant Marsh is located.

3.5.2 Long-term climatic trends

Evidence of natural climate change over substantially longer time periods (hundreds of years, or more) is provided by historic lake levels (discussed in Section 2.5), since these are sensitive to regional climate change through the subtle balance between rainfall and lake evaporation. Of particular interest for this study are historic periods of low lake levels, which would have produced concomitantly low (or no) outflows into the Shire River. They inform about longer-term resilience of the Marsh to severe droughts:

- the complete cessation of flow from Lake Malawi during the early part of the 20th century;
- the “*unquestionable*”[192] evidence of a lower and longer duration level circa 1800; low levels circa 1550 and 1150, which were comparable to the most-recent (early 1900s). Interestingly, though based on a limited number of low levels, is that their frequency may have increased: three in the last 470 years, of which two occurred in the last 200 years.

This demonstrates that within the last one or two millennia, fluctuations of at least 14 m occurred in the lake, which included episodes (four over the last 1 200 years) of no lake outflow. Extending even further back in time, to the scale of lake history,[193] Delvaux (1995) refers to various studies and cites fluctuations as great as 250 to 400 m, which can be explained, in part,[194] by natural climate change. Figure 3.18 is a graph of relative lake level since the late Pliocene to early Pleistocene (1 to 1.6 Ma), redrawn from De Vos (1994). After a high stand of the lake level (~half a million years ago) a stepwise progressive recession occurred between ~0.42 and 0.25 to 0.12 Ma, possibility induced by a major climate change (Delvaux, 1995). A rapid increase followed, with minor short-term fluctuations, to arrive at the status quo. These so-called ‘minor short-term fluctuations’ are relative to the scale of change depicted on the vertical axis. The inset to Figure 3.18, is for 145k[195] years BP (Before Present), and indicates ‘minor’ drops in lake level of up to ~100 m over the past 20k years, with more substantial fluctuations (550 m) between 60k and 145k years BP.

Of particular relevance for this study is that over the long term, i.e., hundreds to hundreds-of-thousands of years[196]:

- lake levels and outflows into the Shire River were relatively high during the latter halves of the last two centuries;
- the cessation of flow from Lake Malawi in the early 1990s, and progressively falling lake levels over decades (Figure 1.9), are not uncommon, and;
- although the effects of anthropogenic-induced climate change are uncertain, the tendency is for increased average annual precipitation

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[191] dealing with how to adapt to the effects of climate change
[192] Nicholson, 1998
[193] 4.5 to 8.6 million years (Delvaux, 1995)
[194] since similar variations were recognised in Lake Tanganyika
[195] thousand
[196] refer to Figure 1.4, Figure 1.5 and Figure 3.18

- that said, projections for moderate decreases seem to be well within the ranges of historic (natural) change.

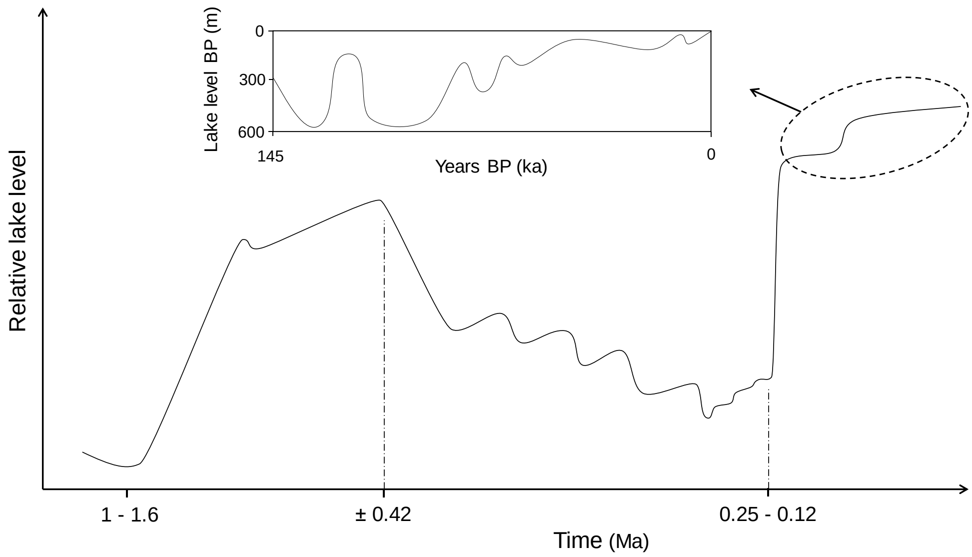


Figure 3.18 Long-term lake level fluctuations redrawn from De Vos, 1994 (as cited by Delvaux, 1995) with the inset for 145k years BP redrawn from Scholz *et al.,* 2011 (Ma is Mega-annum, or million years; ka is kilo-annum or thousand years; BP is Before Present)

Climate change is considered further within Chapter 7 where past trends in the hydromorphological functioning of the Marsh, and its resilience, are discussed. The next three chapters (Chapters 4, 5 and 6) deal with characteristics of the Marsh.

4 Channel change, flooding and landuse/vegetation distributions in the Marsh

This chapter deals with the characterisation of the Marsh, from a physical and vegetation perspective. Historical channel change and flooding are addressed in Section 4.1 and the spatial distribution of landuse and vegetation in Section 4.2.

4.1 Historical channel change and flooding

A series of hydromorphological maps of the Marsh's channels and flooding patterns over time were compiled to develop an understanding of the historical channel change and flooding and to identify recent trends in the hydromorphological behaviour of the Marsh, which can in turn be used to infer its future resilience. The resources used for documenting physical change and landuse/vegetation distributions are summarised in Table 4.1 and discussed in the sections that follow.

4.1.1 Historical channel change

The earliest known (sketch) map of the Elephant Marsh was made by Kirk on the second Shire River expedition of 1859, and is reproduced in Figure 4.1. It shows the Marsh at latitude 16.23° South, between the village of Mankoque[197] and the Ruo River confluence. Maps produced a few years later, with the assistance of cartographers in London and at scales allowing useful interpretation, include Livingstone and Arrowsmith's[198] (oft published) 1865 "*South Eastern African map of the Zambezi River and its tributaries"*, an extract of which is illustrated in Figure 4.2 (top).[199] Salient features noted on the map include the Elephant Marsh, shown predominantly on the northern (left) bank of the Shire River; a few rivers entering the Marsh from the right bank (the Tangazi and Nyangorima are named) and; the overland expedition route up the Shire River along its right bank. A map published two years later by Bellvile,[200] reduced from an original by Livingstone and Thornton, is reproduced in Figure 4.2 (bottom).

Noteworthy are: the greater detail shown for the Shire River flowing through Marsh that reveals a few distributary channels; the Marsh being located on both banks; and most interestingly, tributaries from the north-western mountains (Thyolo Plateau - refer to Figure 4.3) shown as flowing into the Ruo River, with the specific reference "*River according to Mr Waller"*[201] and the broad band of palm trees are shown along the Marsh's northern side. Both the 1865 and 1867 versions indicate a bend in the Shire River at the upstream end of the Marsh (i.e., flowing in a southerly direction), but more so in the latter version. This is not evident in Kirk's earlier (1859) sketch map, which is less detailed.

[197] spelt 'Mankokwe' in the later 1965 and 1867 sketch maps in Figure 4.2. Mankowe's was located close to the Mwanza River confluence, but no references to this village appears after Livingstone's descriptions (refer to Section 2.1)
[198] cartographer
[199] A map produced by Kirk (1865) of Lake Nyassa and the Shire River is almost identical for the section flowing through the marsh, but with the indication of distributary channels. The map also shows a longitudinal profile of the water surface. It is not replicated here as it has only been obtained at lower quality.
[200] cartographer
[201] Mr (Rev. - ordained 1867) Horace Waller was an English anti-slavery activist, missionary and clergyman. He was known as a writer on Africa, an evangelical Christian, a close associate of Livingstone and others involved in central and east African mission and exploration work, and an advocate of British imperial expansion.

Table 4.1 Historical maps, photographs and imagery sourced for mapping channel change, flooding and vegetation distributions

Type	Date of information or authorship	Resolution or scale	Author/source	Other details and figure references	Printed
Hand-drawn	1859		Kirk (National Library of Scotland)	Figure 4.1	
Hand-drawn	1865		Livingstone and Arrowsmith	Figure 4.2	
Hand-drawn	1867	1: 850 000	Bellville, Livingston and Thornton (RGS, London)	Figure 4.2	
Hand-drawn	1893		Sclater (RGS, London)	Figure 4.3	
Hand-drawn	1897	1:126 720	Beringer	Figure 4.4	
Hand-drawn	1898		Johnston (RGS, London)	Figure 4.5	
Aerial photography	29-03-1963	Low	USGS Earth Explorer		
Topographical	1950 to 1974[2,4]/76[3]/77[1]	1:50 000	DoS, Malawi	[1]Chikwawa; [2]Ngabu; [3]Muano Mission; [4]Chiromo; digitised channels indicated in Figure 4.6	1977[2,3]/88[1]/89[4]
Drawn	1953		Morgan	1948 aerial photography; Figure 4.8	
Topographical	1958 to 1960	1:250 000	DoS, Malawi	Nsanje; Sheet 10; Figure 4.9	1975
Aeronautical	unknown to 1965	1:250 000	US (Army Map Service, Corps of Engineers)	Milange, Mozambique; Series 1501 Air; Sheet SE 36-4; Figure 4.9	1979
Landsat LM1	15-08-1973	60 m	USGS EarthExplorer		
Aerial photography	06-07-1977	4.3 m	USGS EarthExplorer	Figure 4.10	
Topographical	Aerial photography 1977, ground survey 1979[5]	1:200 000	Soviet Union (Military Topographic Directorate)	Sheet SE-36-06_Milange_Ed-vtu_1982; Figure 4.10	1982
Landsat LM2	29-08-1979	60 m	USGS EarthExplorer		
Landsat LM5	07-10-1984	60 m	USGS EarthExplorer		
Landsat LM5	16-12-1986	60 m; 30 m	USGS EarthExplorer		
Landsat LT5	01-07-1989	30 m	USGS EarthExplorer		
Landsat LT5	04-05-1997	30 m	USGS EarthExplorer		
Landsat LT5	22-08-1999	30 m	USGS EarthExplorer		

Type	Date of information or authorship	Resolution or scale	Author/source	Other details and figure references	Printed
Landsat LE7	04-03-2001	30 m	USGS EarthExplorer		
EO-1	26-04-2007	30 m	USGS Earth Explorer		
Landsat LC8	10-12-2013	30 m	USGS EarthExplorer		
Landsat LC8	27-11-2014	30 m	USGS EarthExplorer		
RapidEye	22-11-2014	5 m	Blackbridge		
RADARSAT-2	10-01-2015	23 m	ZKI/DLR		
TerraSARX	13-01-2015	9 m	ZKI/DLR		
RapidEye	02-05-2015	5 m	Blackbridge		
Landsat LC8	04-04-2015	30 m	USGS EarthExplorer		

[5] adjacent sheets; RGS = Royal Geographic Society; USGS = United States Geological Survey; DoS = Department of Surveys; LM = Landsat MSS (Multispectral Scanner); LM = Landsat TM (Thematic Mapper); LE = Landsat ETM+ (Enhanced Thematic Mapper Plus); LC = Landsat OLI (Operational Land Imager); EO = Earth Observing; ZKI/DLR = Centre for Satellite based Crisis Information (ZKI) of the German Aerospace Centre (DLR)

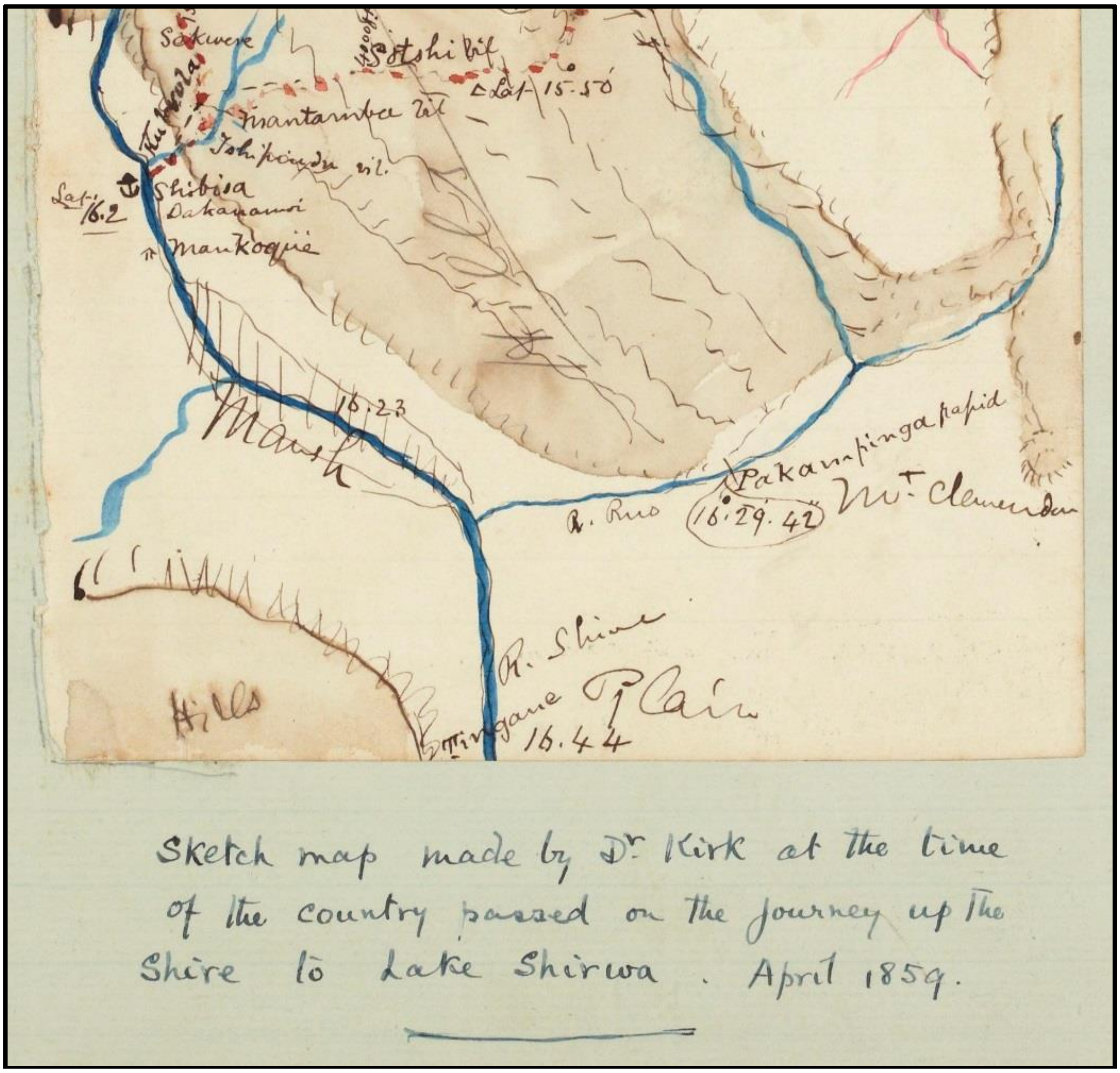
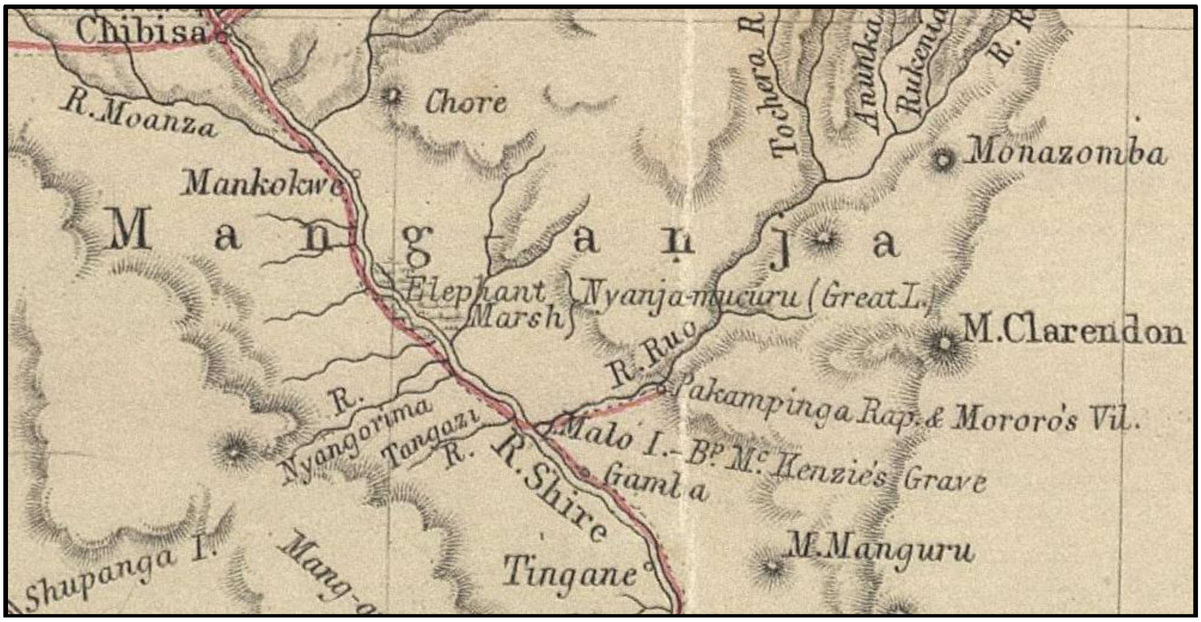


Figure 4.1 **Earliest known sketch map showing the Elephant Marsh made by Kirk on the second Shire River expedition of 1859[202]**

[202] Kirk, John 2, 1832-1922. Sketch Map of River Shire and Lake Shirwa, April 1859. Images copyright National Library of Scotland. Creative Commons Share-alike 2.5 UK: Scotland (https://creativecommons.org/licenses/by-nc-sa/2.5/scotland/).



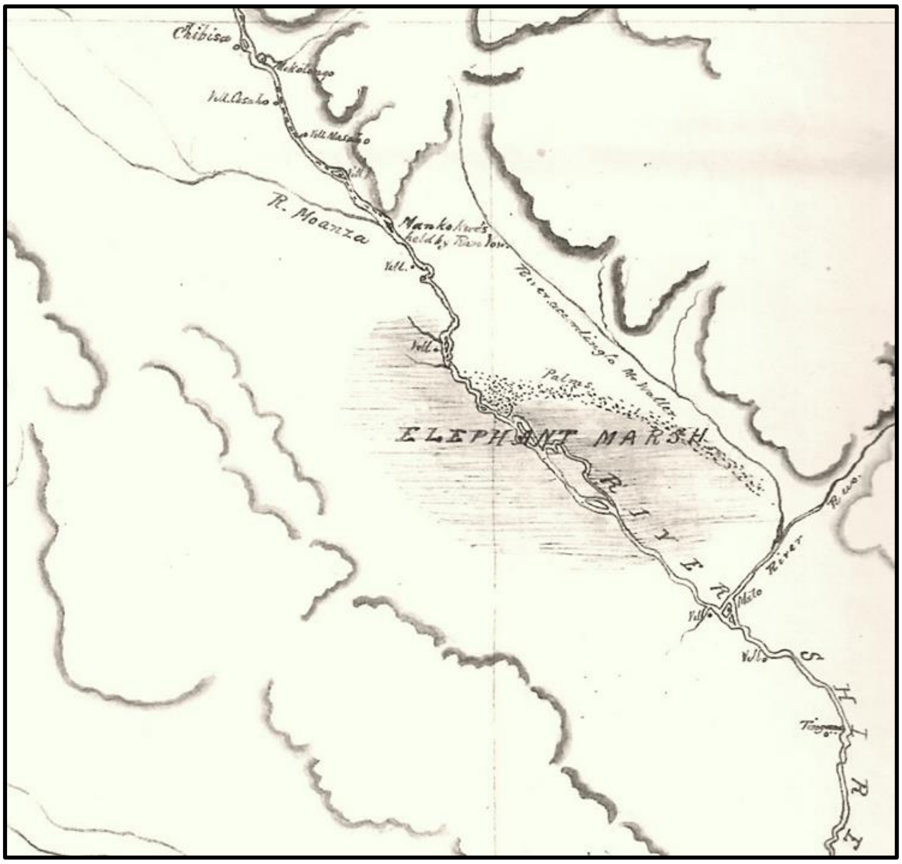


Figure 4.2 Extracts from: top: the well-known 1865 map of Livingstone and Arrowsmith's "*South Eastern Africa: River Shire, the Lakes Nyassa and Shirwa, the lower courses of the Rivers Zambesi, and Rovuma*", showing tributaries flowing into the Marsh and the route (red) followed by the expedition; bottom: the 1867 sketch map of Bellville, Livingstone and Thornton's "*River Shire from Lake Nyassa to the sea*", showing the Marsh with a broad band of palm trees along its north-eastern side (scale 1:850 000)

Three sets of maps were sourced covering the last decade of the 19th century. The first of these is Sclater's 1893 sketch map of the Shire Highlands (a section of which is illustrated in Figure 4.3), which indicates positions and names of villages (*viz*, Chikwawa, Katunga, Masea, Maperera and Makwera[203]), and shows tributaries flowing from the Thyolo Plateau. These are useful for determining the approximate position of the Shire River's course through the Marsh: a south-westerly bend of the Shire River is indicated some distance downstream of Makwera, below which Marsh is illustrated on both banks. Between this point and the Mwanza River, a sizeable area of Marsh is shown on the right bank - the area now occupied by the Nchalo Sucoma Sugar Estate. A further point of interest is the Kizembe River, shown flowing into the Tangazi River, which joins the Shire upstream of the Ruo's confluence. This seems to differ from Beringer's 1897 map published a few years later (Figure 4.4), which indicates the Kazembe River following a more south-westerly route directly into the Shire River at the upstream end of the Marsh. It is possible, though unlikely, that these were different tributaries. It is more probable that tributaries were incorrectly referred to possibly because of the difficulty at that time of discerning and mapping channel routes through the flat topography. From the 1:50 000 scale topographical map based on mid-20th century[204] data (Table 4.1), it seems that the latest naming is the 'Chidzimbi' River. The possibility that the tributaries between this and the Chidima further downstream (refer to Figure 4.6) converged, before flowing into the Shire River's main channel, as indicated (to different degrees) by some maps (*viz*. Belville *et al.,* 1867; Sclater, 1893), is relevant to this study because it supports a conceptual understanding of historic development of lake[205] habitats in the Marsh, in this instance, Lake Tomaninjobi. This is discussed further in Chapter 6 regarding lake sedimentation.

Concerning the tributaries draining the north-eastern catchment (adjacent to the Marsh), it is interesting to note that the Belville *et al.* (1867) map shows their combined flow routing directly into the Ruo River, with specific acknowledgement to '*Mr Waller*'. No other maps indicate this, but neither do they contradict it, since they either refer to a later period (~three decades), or the tributaries are not illustrated (e.g., Livingstone and Arrowsmith, 1863). Therefore, although seemingly inaccurate, it is worth further consideration. The Landsat 2001 and 2015 imagery in Figure 2.15 indicates floodplain channels between the Ruo and Tomaninjobi Lake, which are known to have been historically active during high flows, that overtopped the Ruo's levees.[206] During the 2015 floods, however, one of the channels, which connects directly to Lake Tomaninjobi (2001 image), became the Ruo's new low flow channel, with extensive sedimentation of its former downstream channel (2015 image). The Belville *et al.* (1867) map suggests a paleo-channel, that with a reversal of flow direction conveyed overbank flows from the Ruo (directly into the Elephant Marsh), but which more-recently became the route of its active channel, flowing into Lake Tomaninjobi.

Beringer's map appears to provide little detail for the stretch of Shire flowing through the Marsh, where Marsh is illustrated on both banks between the confluences of the Kazembe and Ruo Rivers. Two settlements, labelled Gombwa and Masongoze, are shown on the Shire River's right and left banks, respectively, towards the upstream end of the Marsh. The 1:50 000 topographical maps indicate the 'Gombwa Pond' north of a village known as Alumenda, and the 'Masongoza' settlement ~2.5 km further north. These are defining features that provided geoferencing for Beringer's map, and the earliest conclusive evidence that the Shire River, in the late 1800s, flowed south of its present route through the Marsh. Although the 1865 and 1867 maps of Livingstone and Arrowsmith, and Belville *et al.,* respectively, support a historic southerly route (*viz*. the upstream bend in the planform geometry, the number of tributaries shown to be flowing directly into the Marsh from the south-east, and Livingstone's expedition route up the right bank), none of these are as conclusive. Sclater's 1893

[203] also spelt 'MaKwira' (Johnston, 1898)
[204] the latest
[205] sometimes referred to a lagoons, pools or ponds
[206] Gavin Quibell, pers. com.

map, which while also indicating a more southerly path through the Marsh, provides the location of a village named 'Goma'. Although it is in the correct latitudinal position, it is on the left bank, and most likely refers to Gombwa Island.[207]

Most of the 19th century maps indicate the Ruo River confluence to be the southern limit of the Marsh. There is a narrowing in the Shire River Valley floor in this region, with the villages of Bangula and Chiromo sited on topographical highs. Upstream of this, the valley floor widens considerably, marking the start of the Marsh.

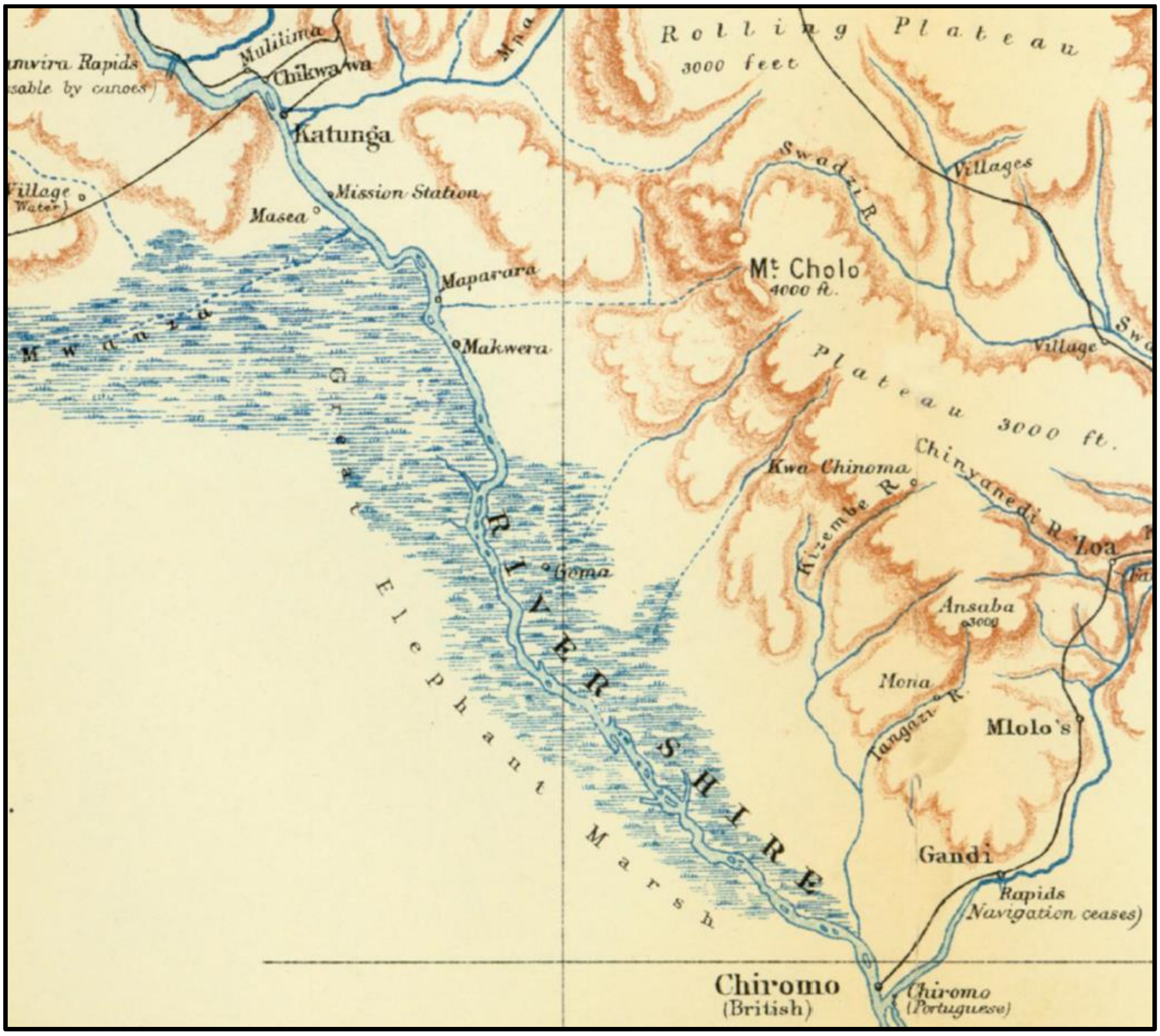


Figure 4.3 **Extract from Sclater's 1893 sketch map of the Shire Highlands, showing routes[208] (black lines) plotted from (his) compass bearings, and astronomical positions of Katunga and Chiromo by Commander Keane**

[207] The latest 1:50 000 topographical maps only indicate Nsua Island.

[208] The cartographers were Turner and Shawe, with the map published by the Royal Geographic Society 1893. Sclater's routes did not include the catchment between Katunga and Chiromo, i.e., the Elephant Marsh.

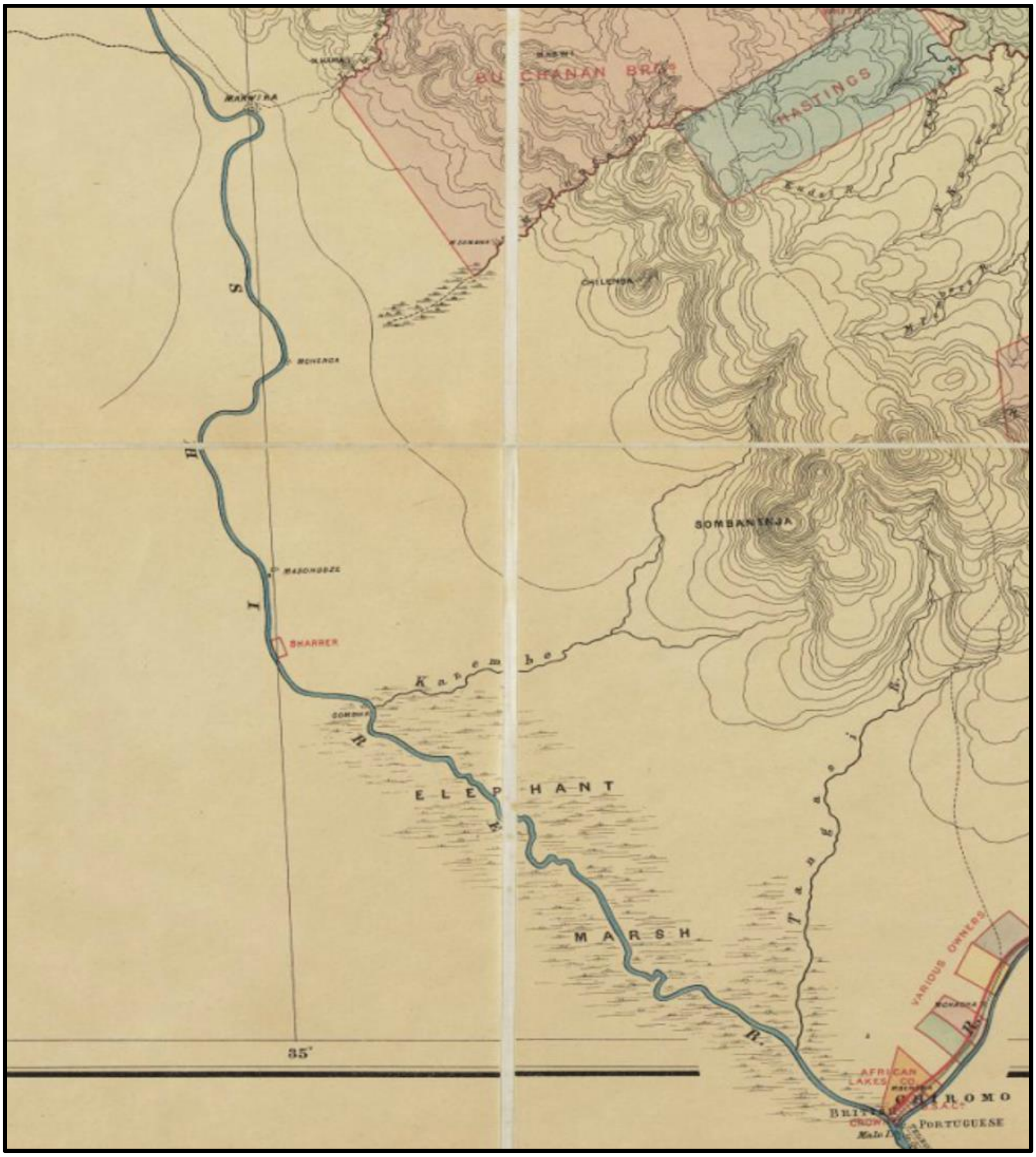


Figure 4.4 Extract from Beringer's 1897 map of the Shire Highlands (scale 1:126 720)

Undoubtedly, the best evidence for the course of the Shire River through the Marsh in the late 1800s are the detailed 1898 sketches produced by Johnston, an example of which is shown in Figure 4.5. Johnston's drawings are well-annotated and show channel directions (relative), widths, distributaries and bars, and include the positions of villages and vegetation (*viz*. phoenix, forest and coconut palms and bananas) along the river banks. Interestingly, Johnston notes the "*End of Elephant Marsh*" near Gombwa, with distributary channels over ~8 km of the downstream stretch. This correlates with the position of a distributary shown by Bellville *et al.* (1867; Figure 4.2). Another defining feature in Johnston's map is the position of the 'Mbenje' settlement towards the downstream end of the Marsh, which was useful, as these 1898 drawings do not have scales, orientations or geographic references. To obtain maximum value from these detailed sketches, the positioning of the Shire River was ~georeferenced using the earliest (and only) available 1:50 000 topographical maps (refer to Table 4.1). The river's planform location corresponds very closely with the Shire River (south-western route) as indicated on the topographical maps, which are based on aerial photography between 1950 and

1977. These planforms are illustrated in Figure 4.6, together with Beringer's 1897 mapping of the Shire River, ~georeferenced. Together, these show that the (main-stem) Shire River followed a course south of Nsua Island during the mid-to-late 1800s. This is significant, since it indicates that the Shire River maintained this course through the Marsh for at least a century.

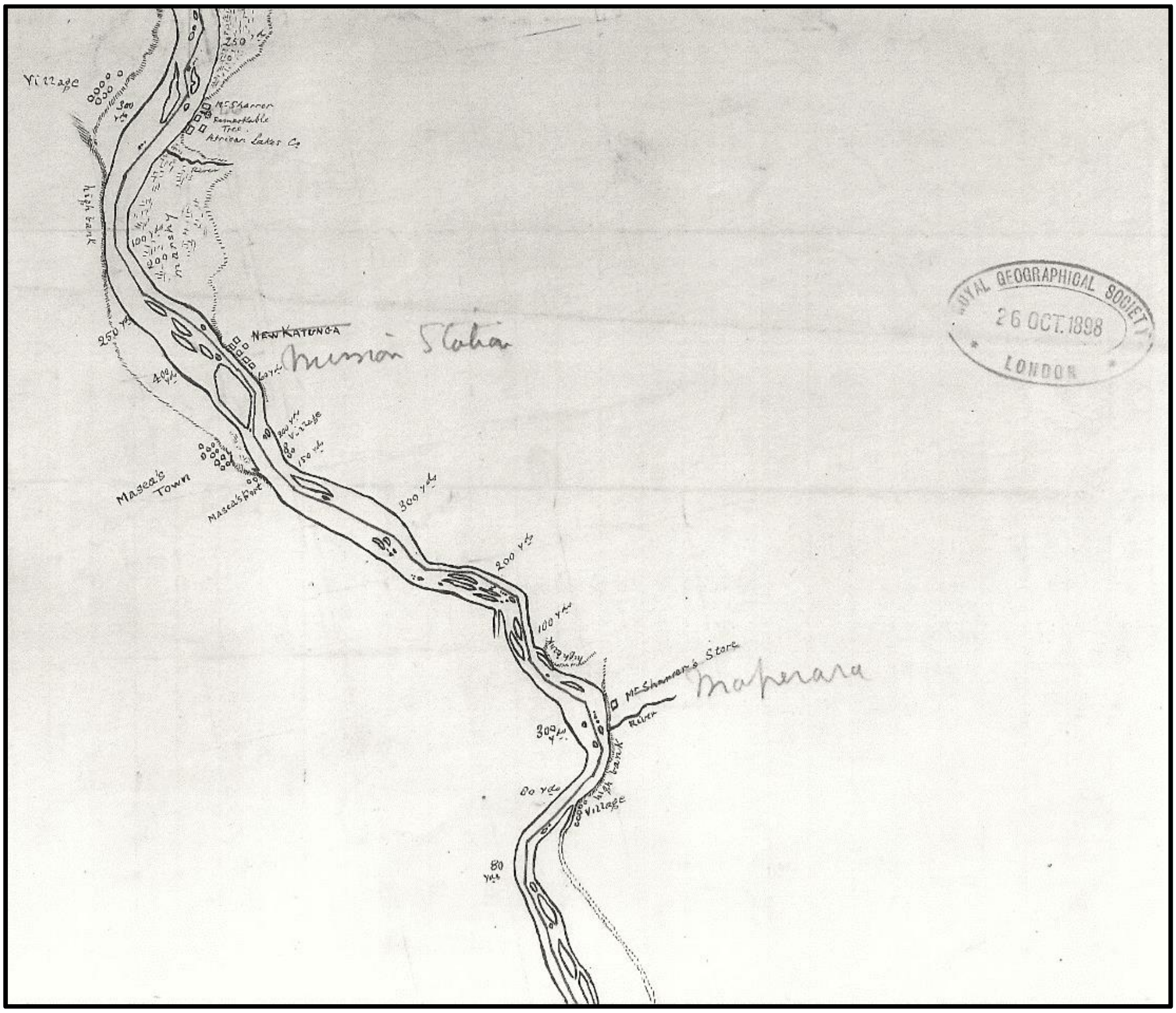


Figure 4.5 **The third sheet from Johnston's 1898 detailed sketch of the Shire River downstream of Chikwawa, showing the location of towns and villages, selected tributaries, channel width (in yards), location of sand bars, and likely the navigable thalweg[209]**

In Figure 4.6, the main-stem sections of the Shire, upstream and downstream of its major diversions, are rendered dark blue; the southern distributary (i.e., the Shire River and channels connected to it) are shaded light blue; the remaining channels, including the northern Namichimba River and its numerous distributaries, as well as the channels south and southeast of Nsua Island, are coloured green. At the downstream end of the Marsh, a minor distributary passes through Bangula Lake, while larger convergent distributaries associated with the Namichimba River route through the more extensive and interconnected north-eastern lake system, which includes Lake Tomaninjobi.

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[209] Johnston was also an artist, hence the high quality and detail of the sketch map of the Shire River's course through the Elephant Marsh.

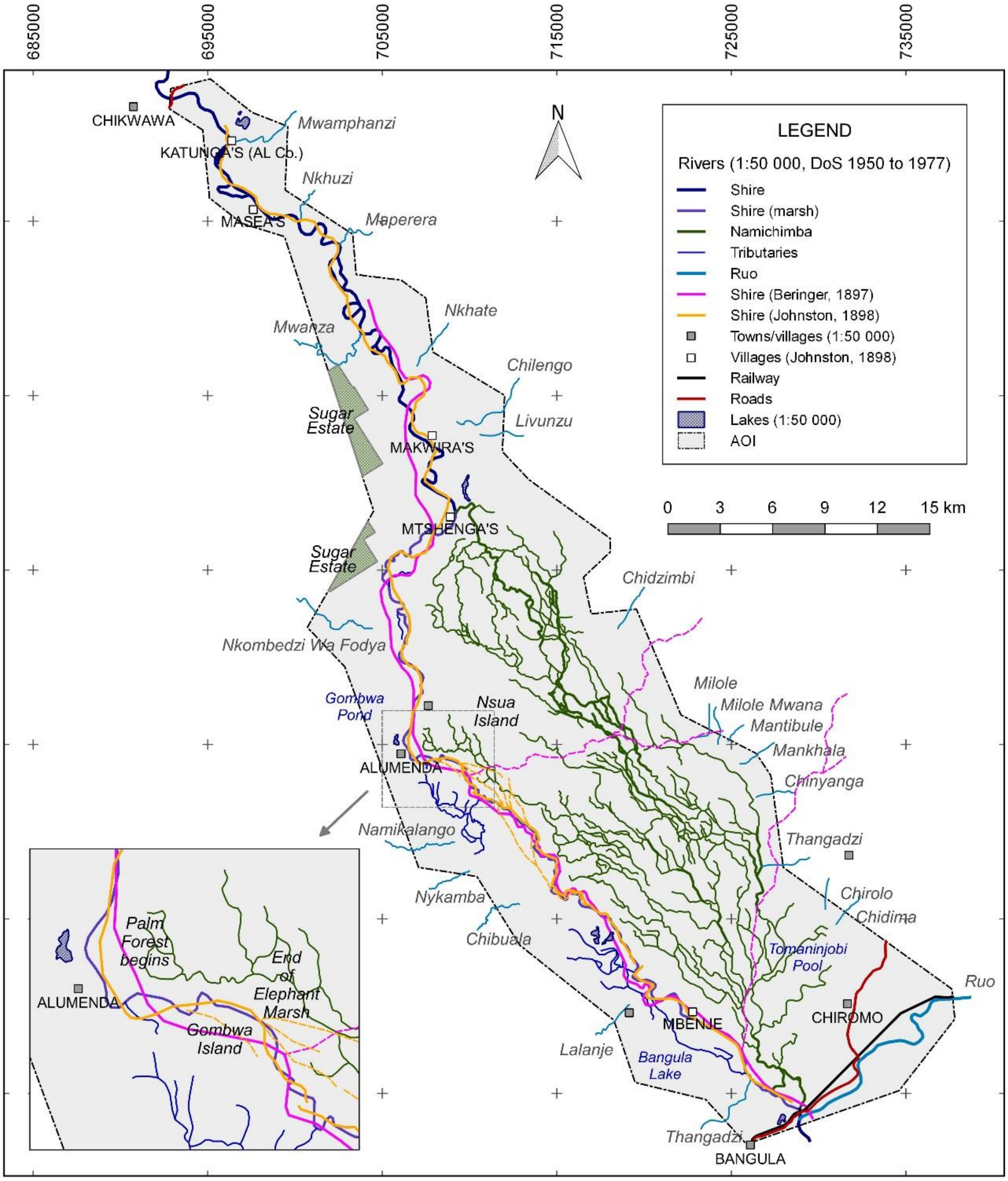

Figure 4.6 **Shire River (main-stem) and its numerous distributaries in the Marsh collectively referred to as the Namichimba channel network (digitised from 1:50 000 scale[210] topographical maps), and the approximate georeferenced position of the river as mapped by Beringer (1897) and as drawn by Johnston (1898); the dotted lines are tributaries (pink) and distributaries (orange); CRS is Arc 1950 (Malawi)**

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210 scanned, georeferenced and merged

Noticeably absent from the all six 19th century maps (Figure 4.1 to Figure 4.5) are the extensive open water bodies, or so-called lakes, lagoons or ponds. Photographs of some of the more extensive lakes, taken in September 2015, are presented in Figure 4.7. It seems implausible that these lakes were missed or passed-over by all the 1800s explorers that travelled through the Marsh. In Section 2.1, reference is made by Livingstone and Livingstone (1893)[211] to the spearing of fish on weed-covered ponds. It seems, however, that this refers to the (greater) Shire wetlands,[212] and that the existence of shallow lakes in the Elephant Marsh circa 1859 is unknown. It is therefore possible that these extensive lake habitats are a more recent morphological feature.

Morgan (1953), in a paper describing the changing system of African agriculture in the lower Shire Valley of Nyasaland, included topographical and landuse maps from which the images in Figure 4.8 were extracted. Morgan visited the area in 1951, but there is a map reference to 'Marsh (dry season 1948)', from which we deduce that the lake outlines were drawn from 1948 aerial photography. These are the earliest sourced maps that show the Tomaninjobi and Bangula Lakes as expansive water bodies; and the Shire River following the south-westerly course through the Marsh, passing through the northern-arm of Lake Bangula. Surprisingly, the 1:50 000 topographical maps (dating from 1950 photography) indicate very few minor open water bodies (Figure 4.6), with the only such features named (in the Marsh) being the Gobwa Pond and the Tomaninjobi Pool.

Larger-scale[213] maps (Figure 4.9 and Figure 4.10) indicate lakes, but assign them varying sizes. The Bangula Lake is barely noticeable in the Department of Surveys (DoS) map, recognisable in the Soviet version, and extensive in the US aeronautical map. The lake-complex north-east of Bangula across the Shire River (and including Tomaninjobi) is smallest in the Soviet map, 'mid-sized' in the DoS map, and extensive in the US aeronautical chart. It would be unwise, however, to infer temporal changes from these maps as they are based on aerial photography spanning a few decades, and possibly from different (hydrological) seasons; and it may have been difficult to discern (and map) lake water-surface extents, due to aquatic vegetation with floating leaves.[214]

The two aerial photographs sourced for this study are dated March 1963 and July 1977 (Table 4.1). The low resolution of the 1963 image does not allow for detailed interpretations of conditions at that date, but both the Bangula and Tomaninjobi lake systems, although indistinct, are visible. The 1977 photography (Figure 4.10, right), supplied[215] at a scanned resolution of 4.3 m, clearly shows the southern lakes. The scanned imagery was processed[216] using a Geographic Information System (GIS), and classified[217] to determine the extent and location of open water bodies, which are illustrated in Figure 4.11. The lakes appear somewhat contracted, which is likely due to the masking effect of floating-leaved aquatic vegetation - a challenge for landcover classification in this environment, which is discussed further in Section 4.2.1. Also, ostensibly turbid Shire River flows, particularly upstream of Chiromo, were not discernible from the photographic image (single-band greyscale rendering of the visible spectrum).

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211 "*Narrative of an expedition to the Zambesi and its tributaries: and of the discovery of the Lakes Shirwa and Nyasa, 1858-1864*"
212 i.e., including the Ndinde floodplains downstream of Chiromo
213 1:200 000 and 1:250 000
214 Aquatic plants may be floating such as the exotic water lettuce *Pistia stratioites* and water hyacinth *Eichhornia crassipes*, or rooted with leaves that float such as the white water lily *Nymphaea lotus* and water chestnut *Trapa natans*. Aquatic vegetation with floating leaves is most relevant to this study, particularly for landcover classification using remote sensing since it masks identification of the water column beneath it. In this report, this is referred to as 'floating-leaved' aquatic vegetation.
215 by the USGS as two 1.2 GB unregistered tiff files
216 cropped to the area of interest, merged and georeferenced
217 Pixels were classified using a threshold value; minor clumps were removed and gaps filled; (potential) regions classified as open water were vectorised; these were filtered using thresholds by proportional area of reflectance values.

Figure 4.7 **Photographs taken in September 2015 (dry season) of some of the more extensive lakes in the Marsh; for location references (a to c) refer to Figure 4.11**

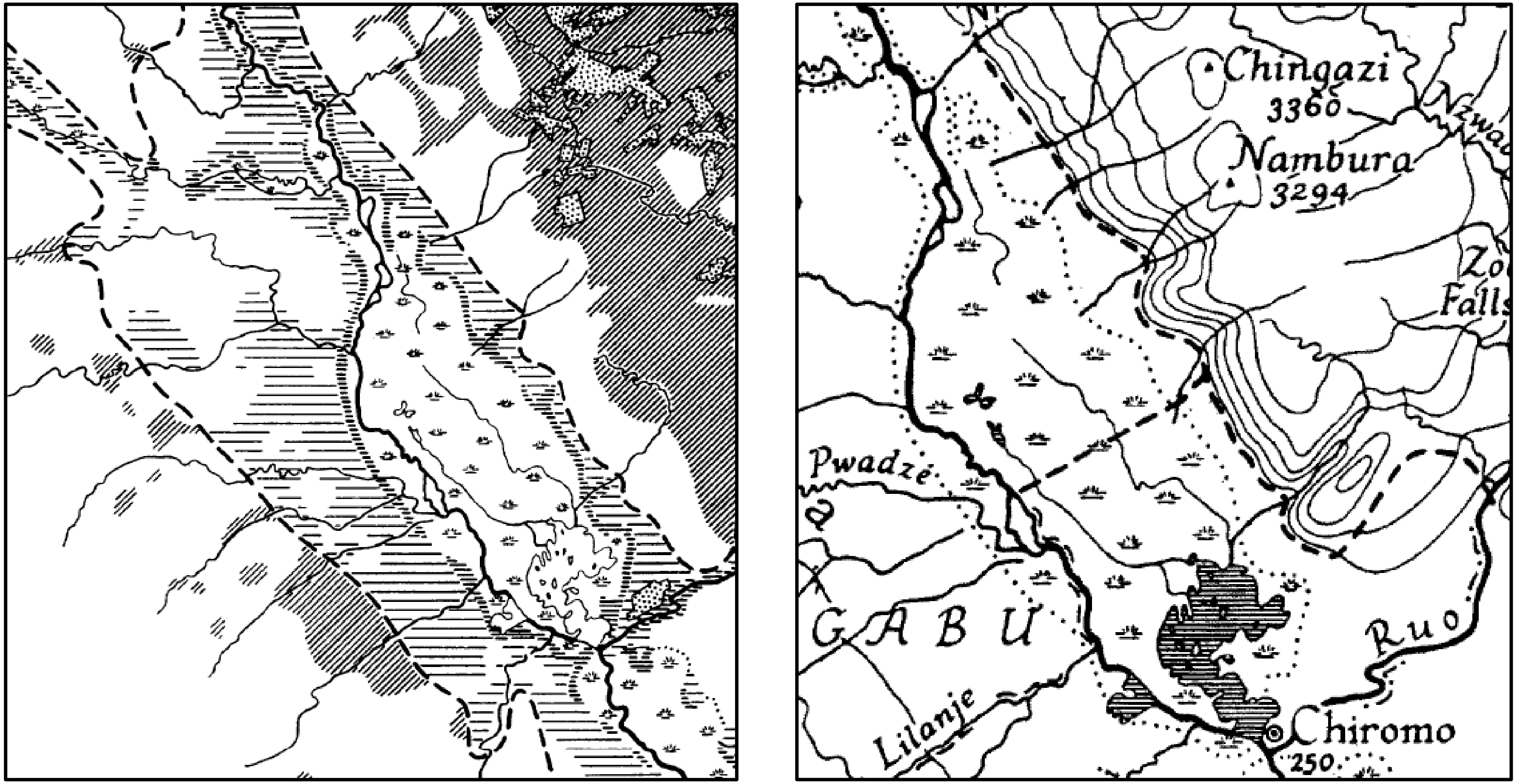
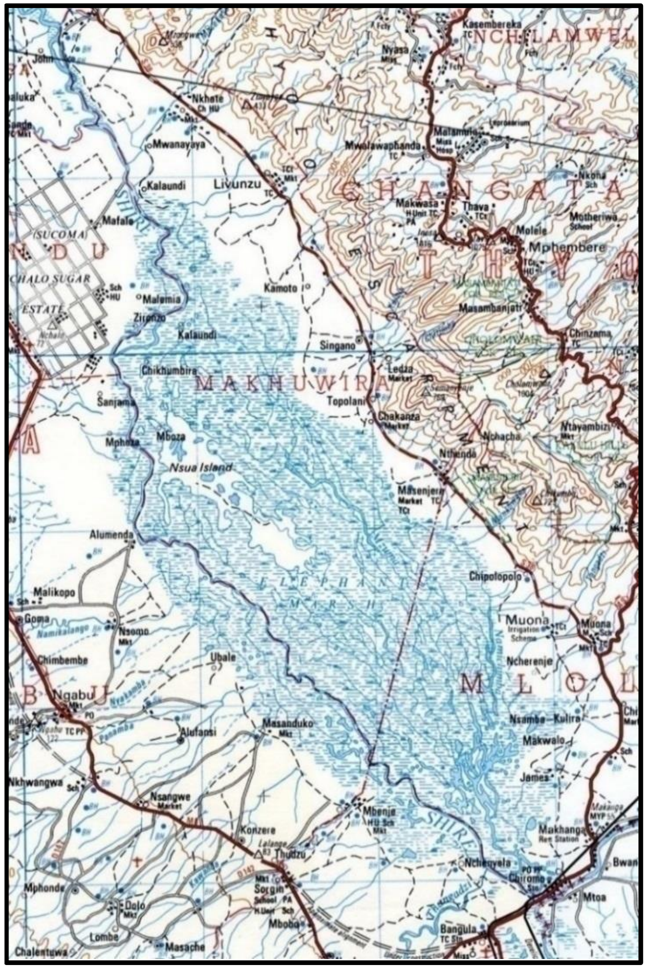


Figure 4.8 **Extracted images of the Marsh indicating, left: surrounding landuse, and right: the lakes in the south-east regions, after Morgan, 1953; the Marsh boundary and lakes were likely drawn using 1948 aerial photography**



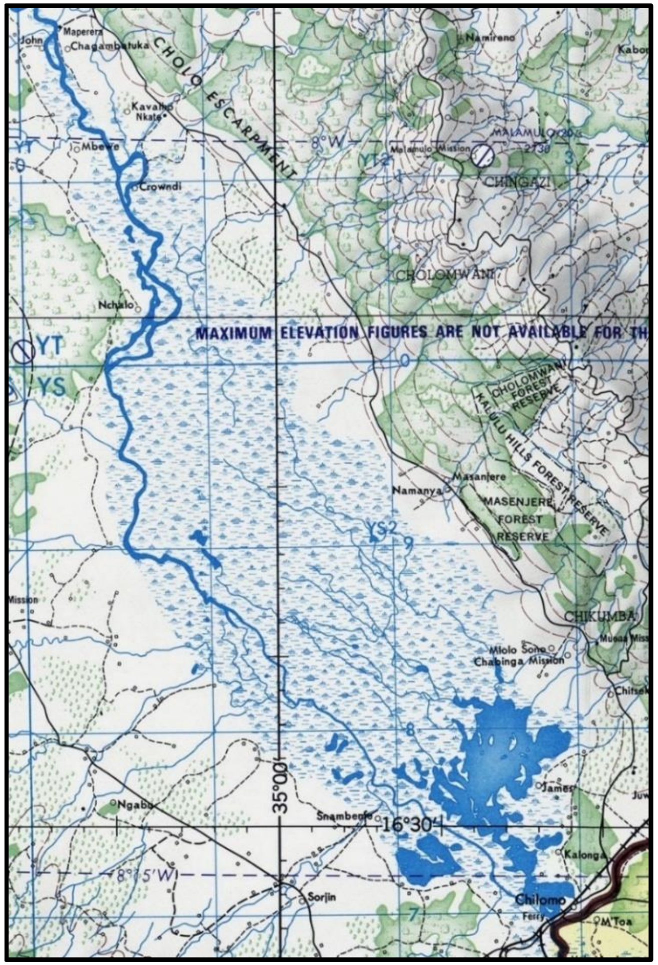


Figure 4.9 **Extracted images of the Marsh from scale 1:250 000 topographical maps; left: DoS (Malawi) based on aerial photography between 1958 and 1960 (printed 1975), right: US aeronautical based on aerial photography to 1965 (printed 1979)**

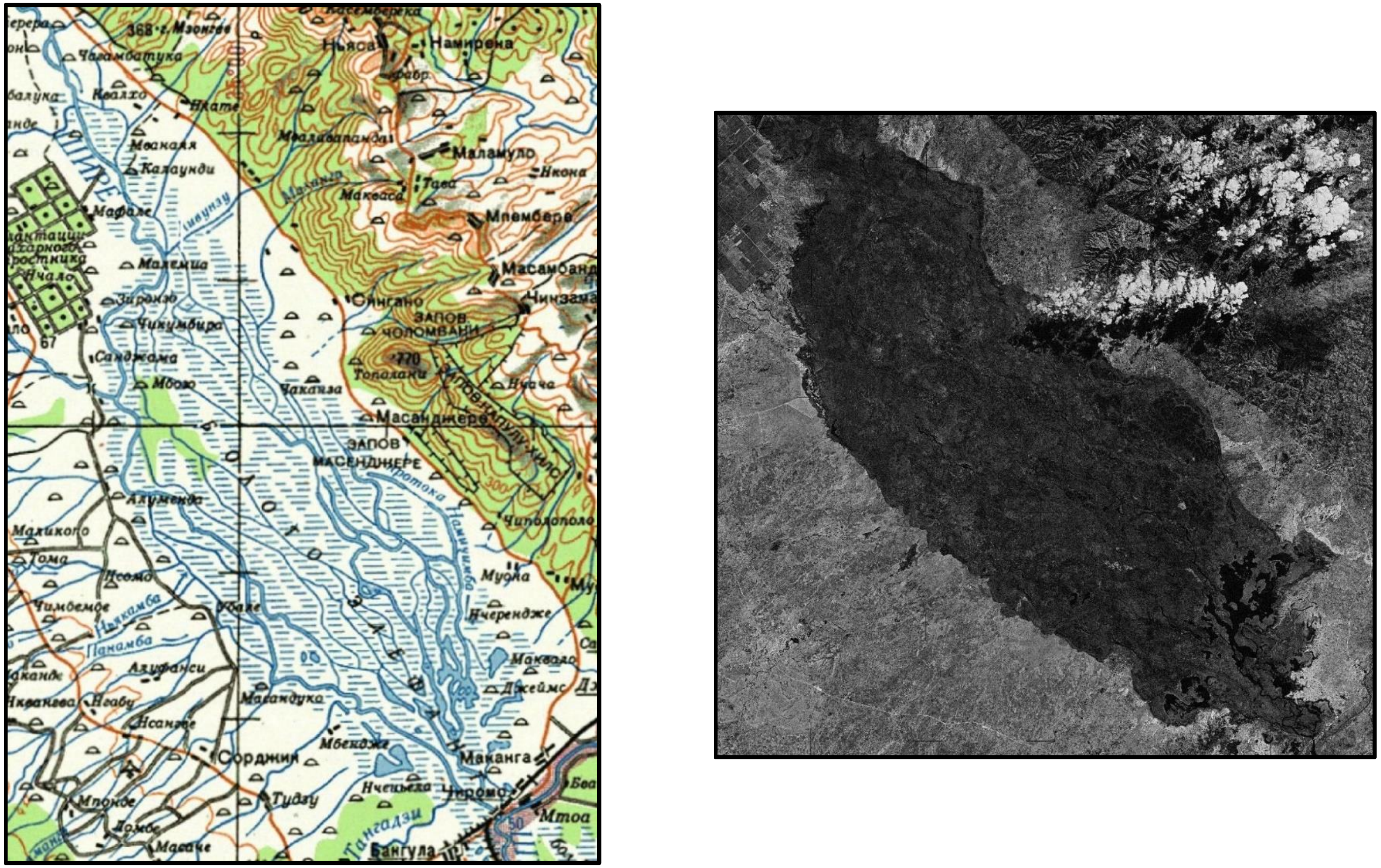


Figure 4.10 **Left: extracted image of the Marsh from a scale 1:200 000 Soviet Union topographical map based of (assumed) 1977 aerial photography (printed 1982); right: 1977 aerial photograph of the Marsh at 4.3 m resolution, showing the open water bodies (dark regions, but note the cloud shadow).**

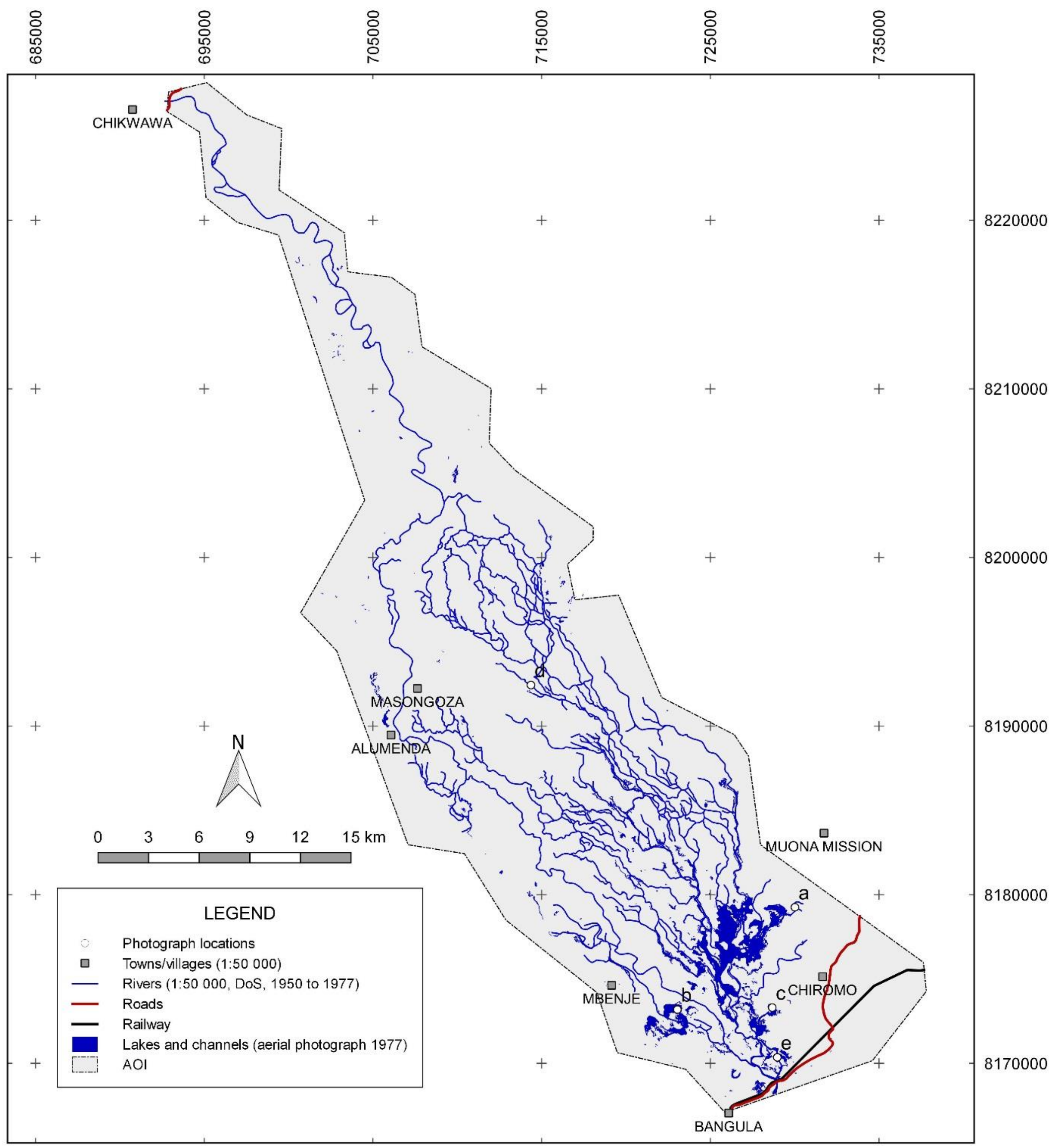


Figure 4.11 Open water bodies (mainly lakes but including wider channels) mapped using the 1977 greyscale aerial photography in Figure 4.10 (right); channels from the 1:50 000 scale topographical maps are also shown, and compare closely with wider channels mapped from the 1977 photography; cross-referencing to photograph locations (a to e) are also indicated; CRS is Arc 1950 (Malawi)

The series of 20th century topographical maps procured for this study are based on aerial photography for the approximate period 1948 to 1977, also, an aerial photograph of reasonable resolution dated July 1977 was acquired. These all indicate a south-westerly course followed by the Shire River through the Marsh, and the presence, although differentially, of the southern lakes. As deduced from the earliest date, there is a 50-year mapping gap at the beginning of the 20th century. During this time, there were two events of significance for the Marsh's hydromorphology, namely, the construction of

Chiromo Bridge and its flanking railway embankment in 1907, and the drought of the early 1900s. These were described in Chapter 2.

It is likely that the damming effect of the railway embankment, mainly during high flows (see Figure 2.10 and Figure 2.11) has substantially contributed to the present character of the southern marsh.[218] The complex interactions between increased inundation (due to backup), enhanced sedimentation, and vegetation response are deemed to have resulted in the southern region accommodating a high proportion of shallow lakes: two-thirds of the open water surfaces occur in the lower one-tenth of the Marsh.[219] Furthermore, given that construction was completed over a century ago, it is expected that backup effects have influenced conditions a considerable distance upstream: almost all the indigenous marsh vegetation (typically papyrus, reeds and grasses) occur in the southern and central/eastern two-thirds of the Marsh.

The Marsh, as it appears today, is a very different landscape to the picture described for the 1900s, such as: "... *no sign of marsh land*...", and "... *never found a trace of water or any indications of marsh* ..." (refer to Chapter 2). There is evidence to suggest that it may also have been less spread-out (than present) during the mid-to-late 1800s. Certainly, give that it allowed for the passage of paddle steamers[220] (Chapter 2) - albeit with some difficulty at times - a more well-defined and wider Shire River channel appears to have existed. The historic south-westerly course with a wider and less obstructed (i.e., higher conveyance) channel would likely have resulted in a drier north-eastern region. This is inferred from the 1867 and 1897 maps reproduced in Figure 4.2 and Figure 4.4, respectively, and supported by results of sediment dating in Section 6.2.3.2.

At the upstream end of the Marsh, the Shire River splits into two channels (Figure 4.11), with the left (eastern) distributary channel named the Namichimba River. Pike and Rimmington (1965) gave the following description: "*The marsh is contiguous with the Shire River, which maintains a channel close to the western margin of the marsh. On the eastern there is evidence of an older channel known in parts as the Namichimba. This channel is to a large extent obstructed by vegetation and silt and is composed of a multiple system of smaller channels and lagoons".* The topographical and aeronautical maps[221] indicate the Namichimba dividing into numerous distributaries, some of which are named (*viz*. the Ntsukamphika, Mwamba, Nzuma and Ntutamasa). The resultant web of channels traverses the north and north-eastern regions of the Marsh, to converge further downstream (again named the Namichimba) before joining the main-stem Shire River about two kilometres upstream of Chiromo Bridge.

The Landsat programme commenced data acquisition in 1972, and is the world's longest collection of space-based moderate resolution land sensing remote sensing data. The earlier images have 60 m resolutions, while those associated with more-recent missions (after 1984), are 30 m. While these resolutions are rather coarse for accurately mapping distributary channels (many of which are narrow) and marsh vegetation-types (refer to Section 4.2), the Landsat archive provided an excellent source for assessing broad-scale changes that have taken place over the last four decades. Based on imagery from 1973 (Table 4.1), the Shire River's main-stem course has altered as follows (refer to Figure 4.12 for channel/location labels A to D):

[218] another factor is the sedimentation of the Ruo River, which is discussed in Section 6.2.3
[219] These (approximate) proportions are derived from

[220] Livingstone's boats had drafts of a metre or more
[221] i.e., covering the period 1950 to 1977

- during the late 1970s and early 1980s, when Shire River flows[222] and concomitant marsh inundation were high, distributary channel/s developed along B, south of Nsua Island, flowing eastwards into the Marsh; the large extent of marsh (in 1979) is evident from Landsat's Near Infrared (NIR) band (for the end of the dry season), shown in Figure 4.13 for 1979 and the substantially diminished marsh in 1999; Figure 4.14 (top) shows a photograph of the Marsh taken in the 1970s, near Nchalo Sugar Estate;
- these channels (along B) formed through the late 1980s at the expensive of the historic Shire River channel along A, which became increasingly abandoned;
- during the late 1980s, a connecting channel developed at D between the Shire River and distributary channels previously associated with the Namichimba channel network; the cut-through is evident in 1986 and is well-developed by late 1989 (floods were experienced in both these years);
- three channels flowing through the upstream portion of the Marsh remained active through the 1990s as indicated in the 1999 Landsat image of Figure 4.15, and;
- subsequent Landsat imagery (e.g., Figure 4.16) shows that the river has abandoned the south-western channel in favour of the (existing) central channel (b).

The progressive abandonment of the south-western channel (c) during the late 20th century is confirmed by Garlick and Killick's 1994 description: "*It seems the Shire is completely blocked now at Alumenda, about ten miles south of Sucoma.*[223] *In any case most of the flow seems to go down the Namichimba where the river divides above Sucoma and this naturally causes much concern on the estate.*''[224]

The reason/s for this change from the Shire River's historic route through the (south-western) Marsh, that dates to at least the mid-19th century, is/are not entirely clear, but are likely related to a combination of factors. These likely include: aggradation of the historic channel bed associated with declining, followed by very low base flows during the 1980s and 1990s, respectively (refer to Figure 3.8);[225] development of the (alternate) distributary channel/s along B (Figure 4.12) during the high flows of the 1970s and early 1980s; the effects of floods; and anthropogenic influences. Concerning the latter, anecdotal evidence[226] is that after the cut-through channel (at D in Figure 4.12) developed through the 1990s, there was associated local human action to impede flow through the southern (Alumenda) distributary (at C). The reasons given for this were the undesirable presence of crocodiles along this distributary and flooding of cultivated lands, and these were acted-upon by planting vegetation to stabilise and promote aggradation of the channel bed immediately downstream of the river diversion. The contribution of this interference to the status quo can only be surmised. The southern distributary is effectively blocked (Figure 4.17, top), and an excavated canal is maintained from the right bank of the Shire River (Figure 4.17, bottom) to supply water to the Alumenda Sugar Estate.

While the 1999 image shows a contiguous channel associated with the Namichimba in the north-eastern region of the Marsh (*viz*. channel 'a' in Figure 4.15), a description of its more-recent character is still well encapsulated by Pike and Rimmington's 1965 account: "...*channel is to a large extent obstructed by vegetation and silt and is composed of a multiple system of smaller channels and*

[222] base and high flows/floods, as modelled at Chikwawa - refer to Figure 3.8
[223] Nchalo Sucoma Sugar Estate
[224] Presently, the central channel (b) is the main distributary.
[225] This is supported by inferences from the hydrodynamic modelling of stage heights at the Chikwawa and Chiromo hydrometric stations (refer to Section 5.4 and Chapter 6)
[226] Kondwani Thawani (skipper, Shire River Crocodiles Ltd), pers. com.

lagoons". The upper reach of the Namichimba[227] was eminently navigable with a small motorized boat in September 2015 during a (Shire River) flow of 190 m^3/s (Figure 4.18). The channel narrows considerably with distance downstream as distributaries develop and flow moves laterally into fringing marsh vegetation.

The most-recent high-resolution imagery covering the entire Marsh[228] is from SEPRET's 2013 aerial survey used to develop a Digital Elevation Model (DEM) for the Marsh, used in the hydrodynamic modelling (refer to Section 5.2.2). Figure 4.20 shows a section of the reach between Chikwawa and the Marsh from SEPRET's orthophotography. The main channels were digitised and are plotted in Figure 4.12, together with those from the 1:50 000-scale topographical maps.[229] The channel overlays illustrate the dynamic nature of channel courses in the Marsh, and along the upstream reach towards Chikwawa.

The upstream reach between Chikwawa and the Marsh (refer to the photographs in Figure 4.21) displays textbook floodplain behaviour, and is characterised by a wide[230] meandering channel pattern that is incised into the alluvial sediments of the adjacent floodplain (Figure 4.20). Bank undercutting at outer bends and sediment deposition at inner bends (developing point bars) are prevalent and have generated lateral channel movement and the formation of convoluted planform geometries. Lateral channel migration and cut-off bends (during flooding) have resulted in paleo channels and depressions across the floodplain, which is also heavily cultivated. Tributaries along this reach include the Mwamphanzi, Maperera and Mwanza (refer to Figure 4.6).

Associated with the substantial change in course of the Shire River's main-stem, and to be expected in marsh environments, the distributary channel network has displayed a highly dynamic planform over the last 75 years or so (Figure 4.12). This results from the complex, seemingly chaotic, interactions between flow and sediment regimes, inundation patterns, sediment trapping and vegetation response. Direct[231] human interventions in the Marsh (*viz*. cultivation and channel modification)[232] have also contributed. This is discussed further in Chapter 7, with respect to future resilience of the Marsh. Essentially, the planforms of some distributaries have been stable; a few have coalesced to form the Shire River's present day main-stem course; but most have been abandoned, with some leaving indications[233] of paleo channels.

The main-stem channel through the Marsh, digitised from SEPRET's 2013 photography, was used to navigate a route from Chikwawa to Chiromo through the Marsh in September 2015. Despite the extremely high intervening floods (of January 2015), the 2012-mapped course was navigated at a reasonably low flow of 190 m^3/s [234] (Figure 4.22). While the Shire River's course is generally well-defined and was eminently navigable for most of its length (using a small boat with an outboard engine), shallow depths[235] made passage difficult along stretches of a reach ~20 km long in the central/southern region of the Marsh. Along this reach, there is a short (~3 km) stretch where the channel is shallow, only a few metres wide, and the adjacent marsh is easily inundated, which was the

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[227] only 6.5 km could be covered
[228] There is high resolution Google Earth imagery from various satellites, but coverage is not for the entire marsh on the same date.
[229] i.e., from the period 1950 to 1977
[230] up to a few hundred metres
[231] indirect impacts include, *inter alia*, flow regulation, increased sediment yield from upstream and adjacent catchments, construction activities (*viz*. Chiromo railway embankment), etc.
[232] as described for the 'Alumenda blockage'
[233] typically through disconnected water bodies and different vegetation patterns
[234] certainly for present day conditions - refer to Figure 3.8
[235] less than 50 cm

only stretch with no visible sign of cultivation or human activities alongside the channel from the Shire-Namichimba split to Chiromo - a river distance of ~60 km.[236]

There is a stretch of channel of ~20 km in the eastern/southern marsh that has remained reasonably stable over the past half-century. This channel includes a section of the downstream Namichimba distributary, which flows through Lake Tomaninjobi to the Shire River confluence, and continues as the Shire River under Chiromo Bridge. A likely reason for its more stable course is a lower sediment concentration, due to the sediment trapping efficiency of the upstream marsh (associated with the Namichimba channel network). The lower sediment concentrations also result in deeper channels,[237] which exceeded 4 m (on average) along the 8.5 km stretch between Lake Tomaninjobi and the Shire River confluence.[238] Downstream of the confluence, the Chiromo Bridge has controlled planform migration of the Shire River since 1908, but this changed with the breaching of the railway embankment in the 1990s.

There are two recent changes that have implications for the morphology of the southern marsh. The first of these is the formation (and progressive erosion) of the alternate Shire River channel through the breached railway embankment near Bangula (Figure 2.11 and Figure 2.13). The breach and active channel passing through it reduce the damming (or backup) effect of the embankment, which results in lower water levels for some distance upstream (i.e., less inundation). The river is favouring this right-bank channel, which is deeper and conveys more flow (Figure 4.23u). The spatial extent of downcutting should be localised, however, controlled by the bed level up to ~8.5 km downstream, where the channel re-joins its previous course. Depending on the level of equilibrium presently attained, upstream inundation may be further reduced in the future. Over longer time frames, however, it is expected that the alternate Shire River channel will aggrade, particularly during floods,[239] and especially given the Ruo River's 2015 re-routing directly into Lake Tomaninjobi. The latter is the second recent change (mentioned above), and is clearly illustrated in the recent (28 October 2016) Sentinel-2A image of Figure 4.24.

The Ruo River transports substantial sediment (Section 6.2), and its altered course through the Marsh, particularly into (shallow) Lake Tomaninjobi, means that sediment will be deposited in the Marsh, commencing with this lake. This has already taken place, with the satellite imagery in Figure 4.25 revealing already considerable diminution of the north-eastern extent of Lake Tomaninjobi. Assuming the Ruo River maintains its altered course through the Marsh through this lake,[240] the projected future for the south-eastern region of the Marsh, including its most expansive lake, is extensive sedimentation and concomitant loss of marsh habitat. It is very unlikely that the Namichimba channel network's (present) ability to deliver sediment-filtered flows will avert large-scale siltation of the lake, as well as sedimentation of downstream channels.

[236] banks are only a few decimetres high
[237] measured using sonar - refer to Section 5.3.3
[238] at a Shire River discharge of ~190 m^3/s (September 2015)
[239] lower relative trapping efficiency of the marsh during high flows
[240] As mentioned in Section 2.3, there are considerations of engineering the Ruo River to return it to its pre-2015 course.

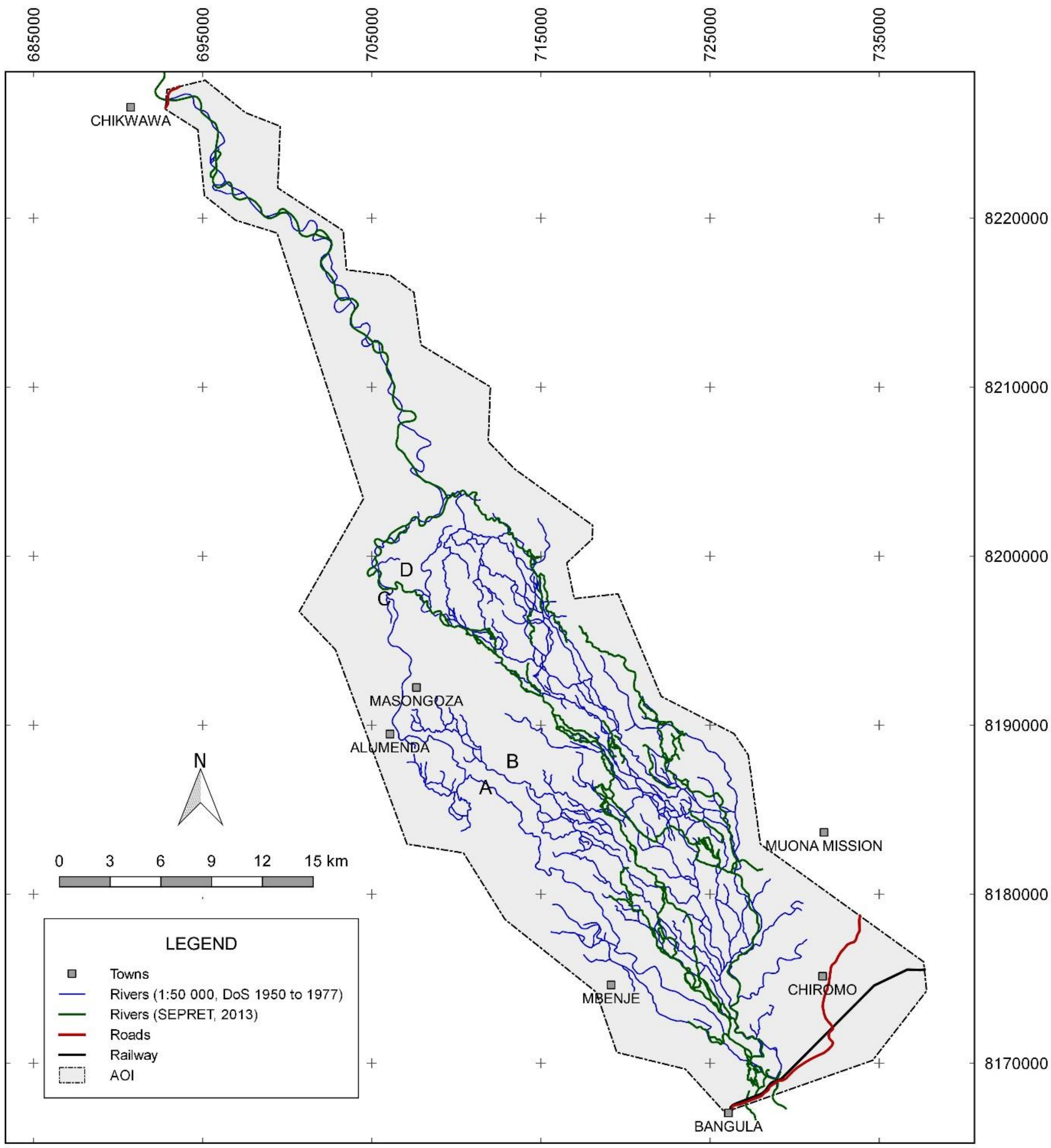

Figure 4.12 **Shire River channels reproduced from 1:50 000 scale topographical maps derived from aerial photographs between 1950 to 1977, and as digitised from SEPRET's 2013 aerial photography; CRS is Arc 1950 (Malawi)**

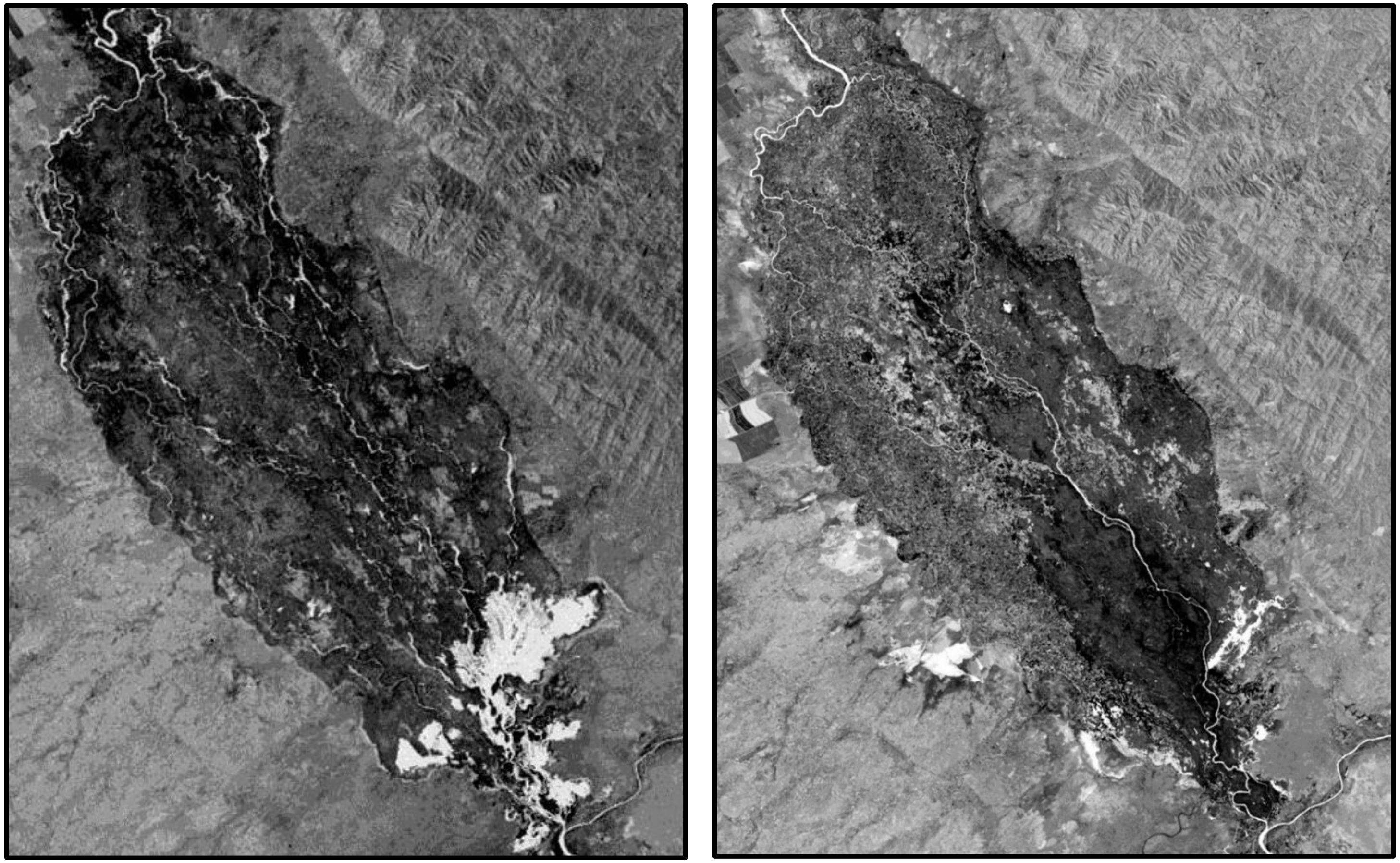

Figure 4.13 Left: August 1979 Landsat 2 NIR (Near Infrared, Band 7); right: August 1999 Landsat 5 NIR (Band 4); high reflectance is indicated by dark shading; water as well as burnt/bare areas are rendered in white (low reflectances)[241]

[241] note, shading is reversed to that used in Figure 4.15 and Figure 4.16

Figure 4.14 **Shire River near the Nchalo Sucoma Sugar Estate. Top: circa 1976 (after Arnoso, 1976); bottom: extensive cultivation of the floodplain and the Alumenda diversion canal which directs flow into the substantially narrowed (historic) course of the Shire for downstream abstraction at Alumenda Sugar Estate (GE, 2013)**

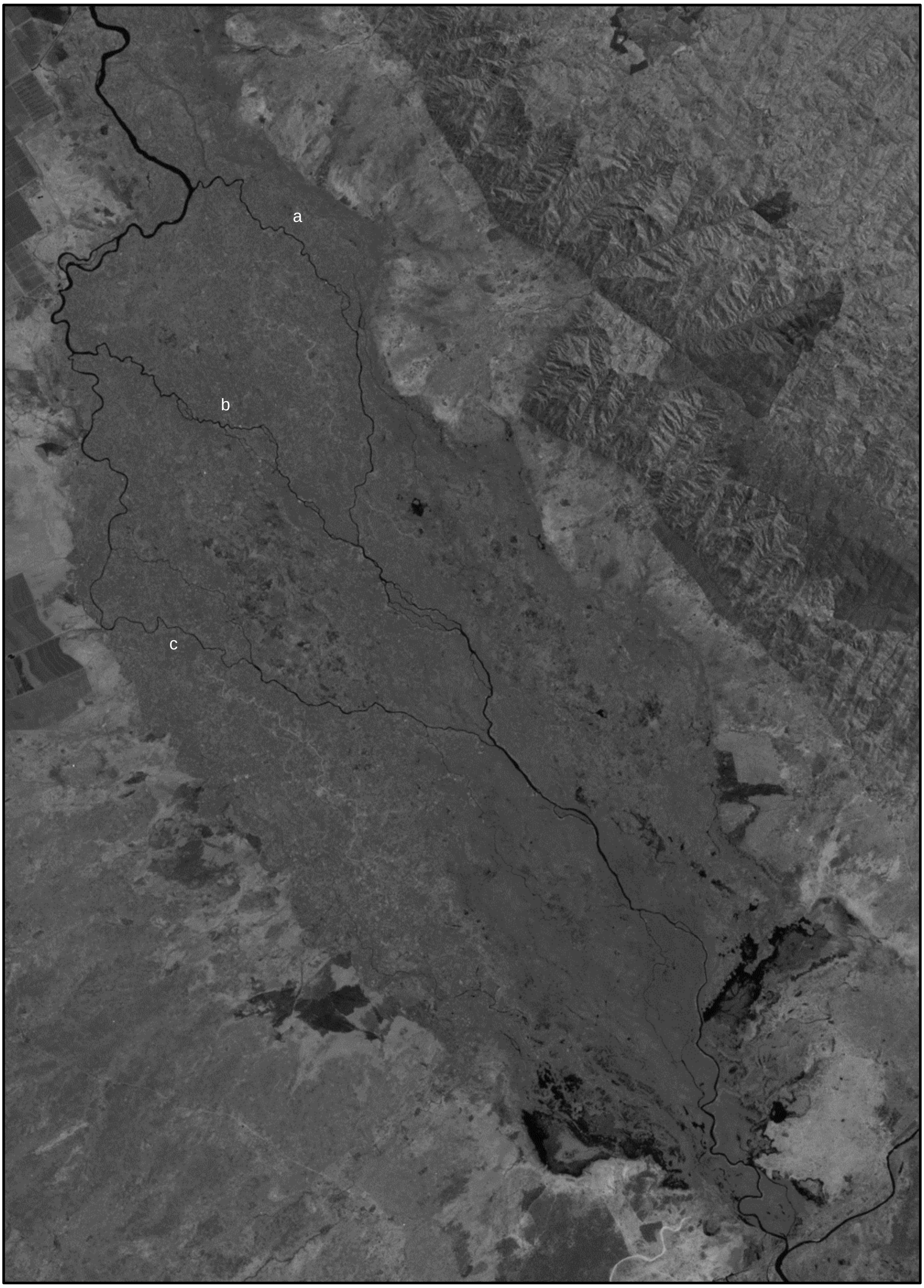

Figure 4.15 August 1999 Landsat 5 SWIR 1 (Shortwave Infrared 1, Band 5); water is indicated by very dark shading; a to c are distributary channels: (a) the north-eastern Namichimba distributary, (b) the more-recently formed central cut-through channel, and (c) the south-western distributary

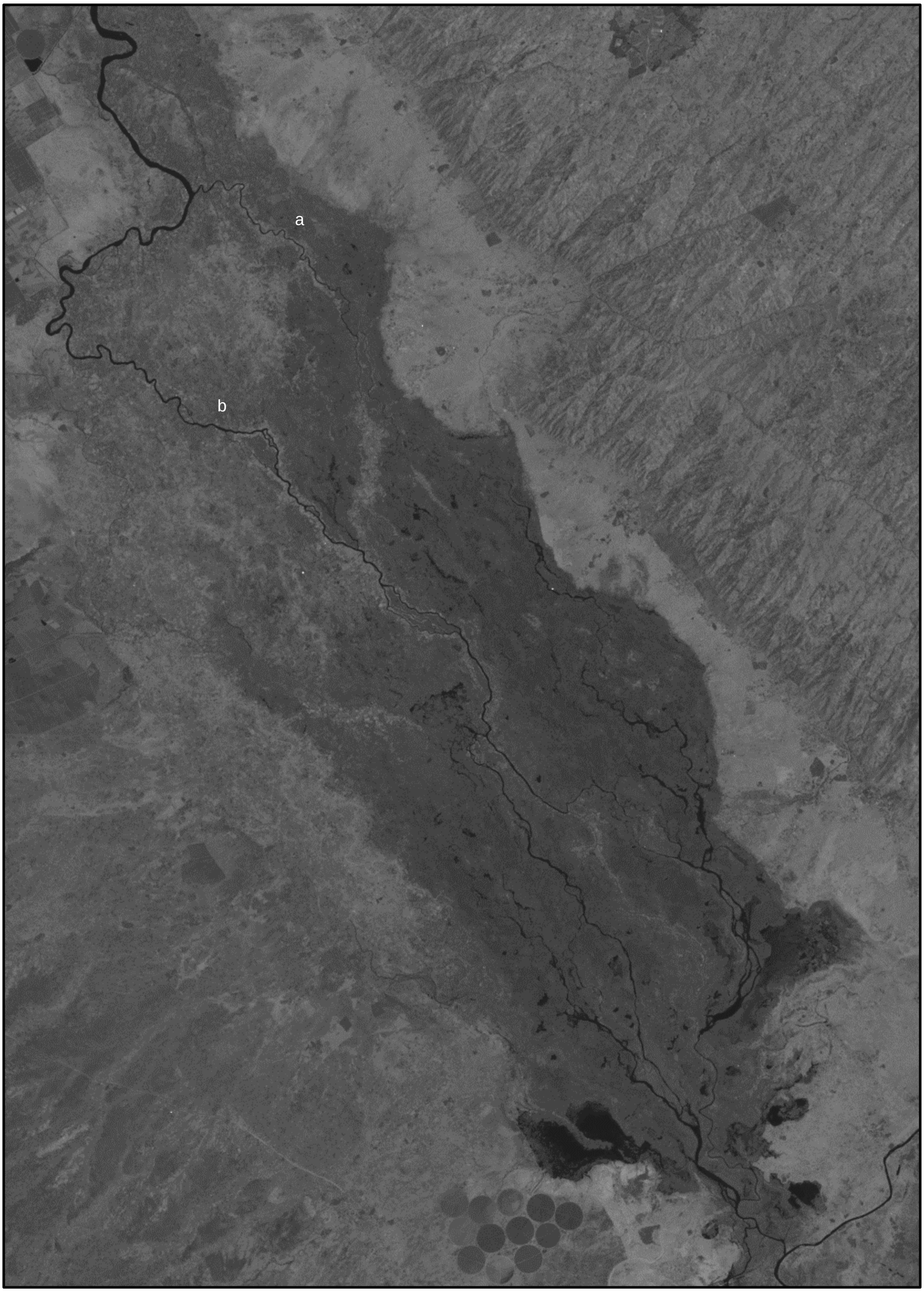

Figure 4.16 **December 2013 Landsat 8 SWIR 1 (Band 6); water is indicated by very dark shading; a and b are distributary channels: (a) the north-eastern Namichimba distributary, (b) a more-recently formed central cut-through channel**

Figure 4.17 **j: the aggraded and vegetated (historic) entry to the southern 'Alumenda' distributary; i: the entry to the excavated canal that diverts flow to the Alumenda Sugar Estate (photographs 1 October 2015); refer to Figure 4.14 (bottom) and Figure 4.19**

Figure 4.18 **Photograph (29 September 2015) of the upper reach of the Namichimba taken from a small boat; refer to Figure 4.19**

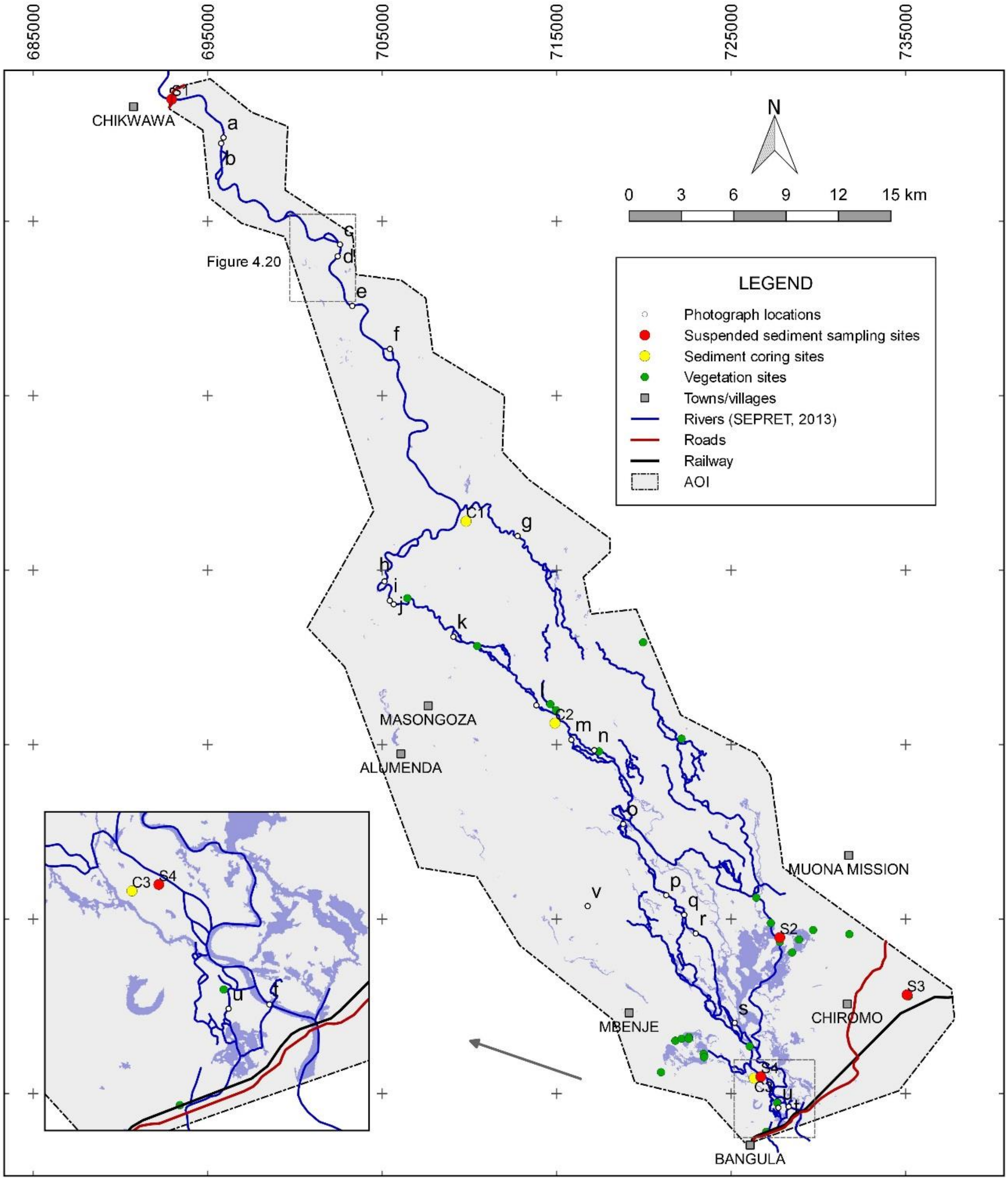

Figure 4.19 **The locations of photograph illustrations in this report and the positions of vegetation, sediment coring and suspended sediment sampling sites; CRS is Arc 1950 (Malawi)**

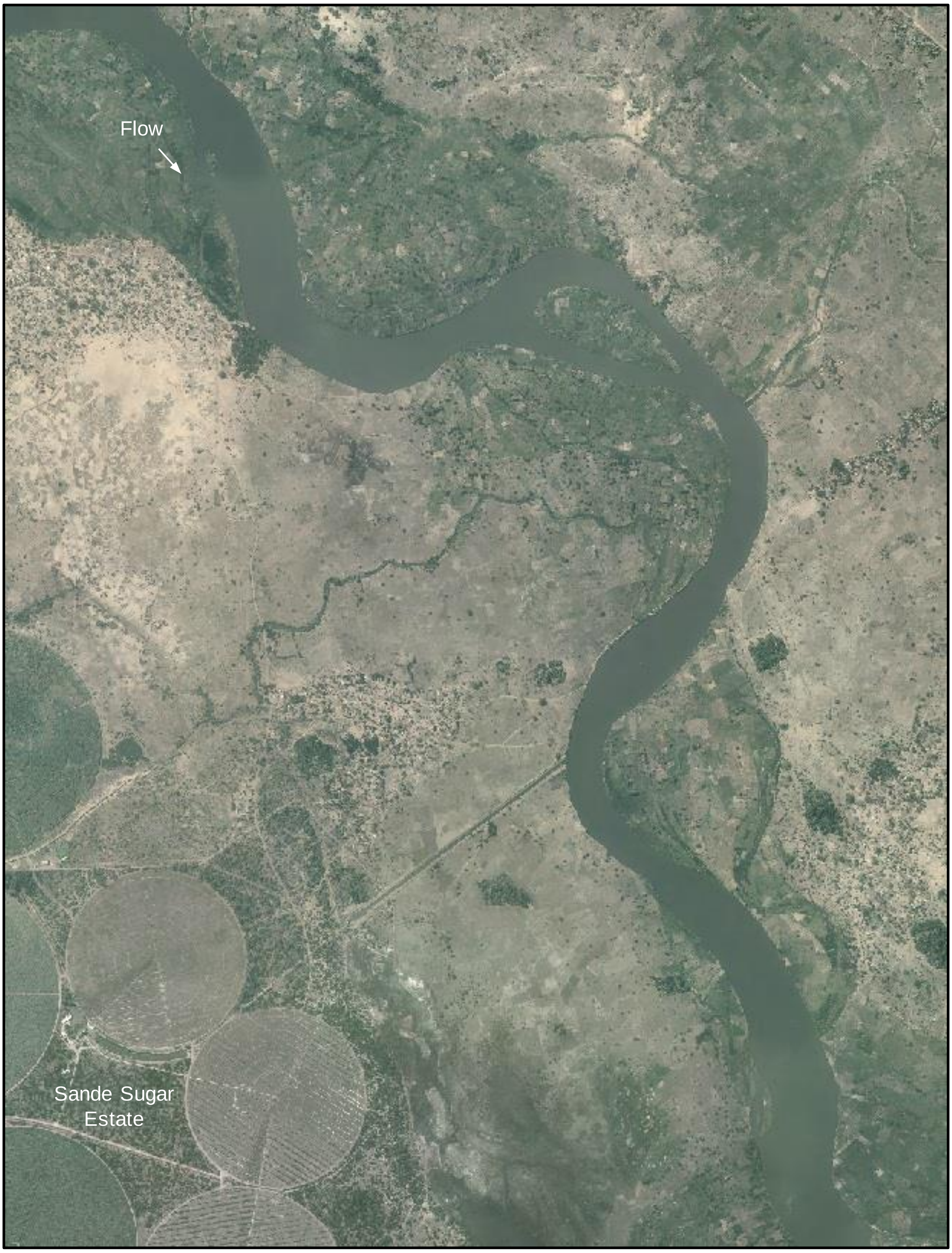

Figure 4.20 **Extract from SEPRET's 2013 georeferenced aerial photography, showing a reach of the Shire River between Chikwawa and the Marsh**

Figure 4.21 Photographs (29 September 2015) from the Shire River reach between Chikwawa and the Marsh: a: looking up the Mwamphanzi River; b: vegetated point bar; c: looking up the Maperera[242] River; d: vertical extent of some river banks; e and f: heavily cultivated floodplain along river banks; refer to Figure 4.19

[242] The view up the Maperera River is partially obscured by a wooden fence-line along the confluence, along which fish traps have been placed; the Thyolo Mountain range is in the distance

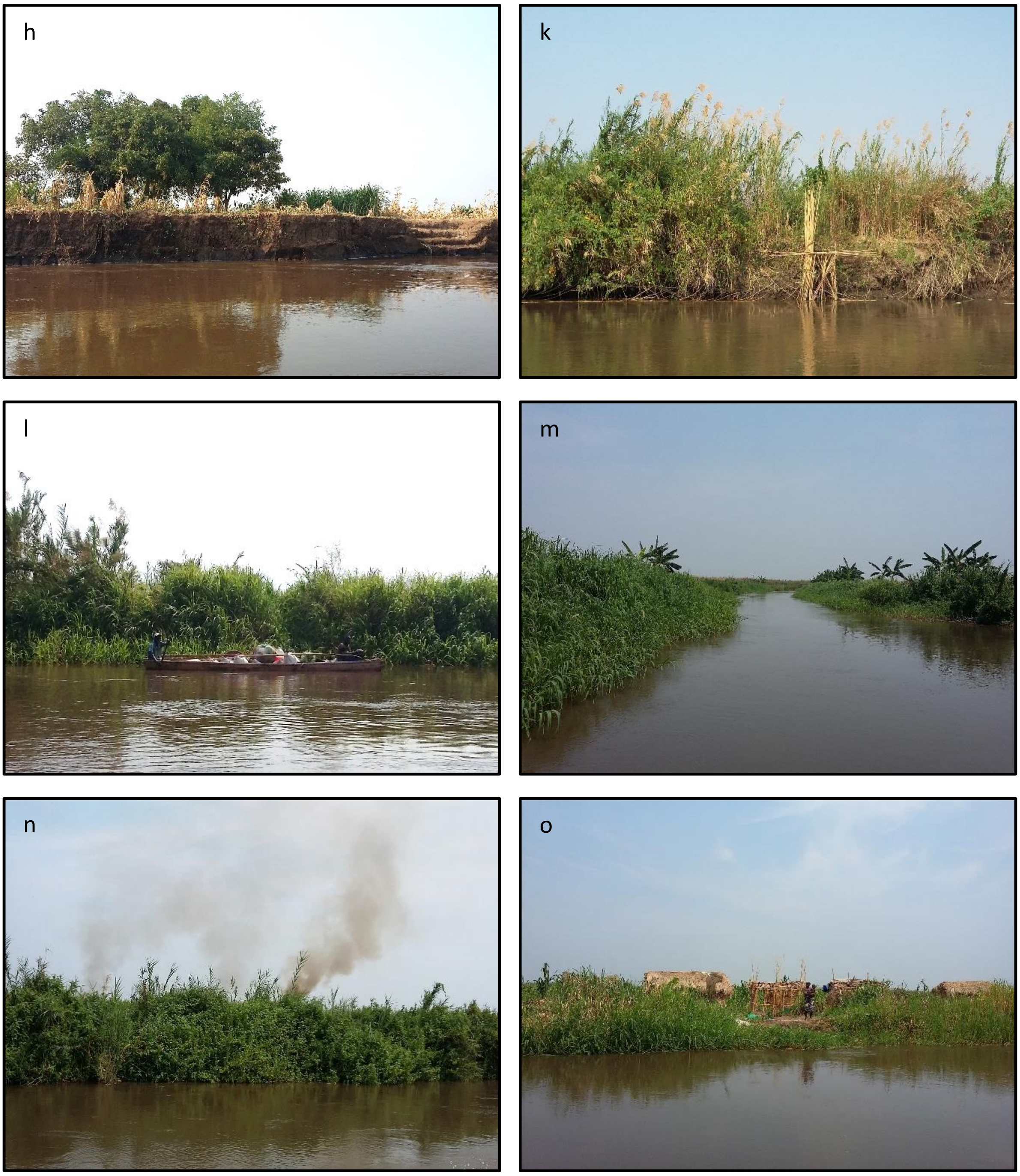

Figure 4.22 Photographs (1 October 2015) taken along the Shire River main-stem channel between Nchalo Sucoma Sugar Estate and Chiromo Bridge; h: cultivated lands and trees adjacent to vertical banks with excavated steps for river access; k: temporary fishing jetty constructed from reeds; l: transporting goods along the river; m: a main-stem distributary channel with adjacent banana trees; n: burning in the marsh; o: temporary dwellings on low banks with cultivation beyond (maize); refer to Figure 4.19

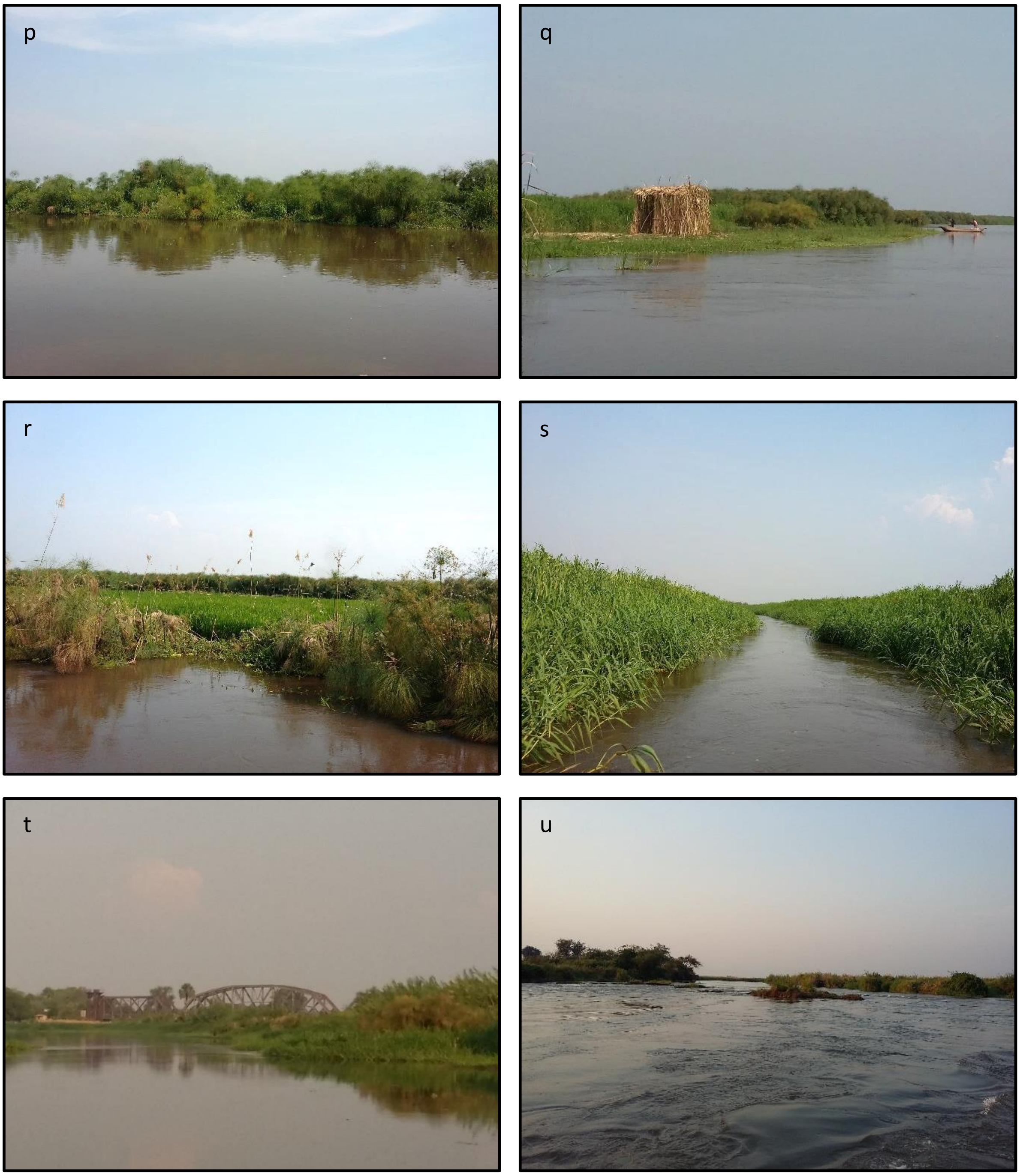

Figure 4.23 **Photographs (1 October 2015) taken along the Shire River main-stem channel between Nchalo Sucoma Sugar Estate and Chiromo Bridge; p: papyrus along the channel margin; q: temporary dwelling on channel margin a few decimetres above the water level; r: rice paddy adjacent to the river; s: narrow/shallow main-stem channel; t: wider downstream channel with Chiromo Bridge in the distance; u: alternate Shire River channel flowing towards the breached embankment (note the turbulence, indicating rapid flow through this area of active downcutting through consolidated sediments); refer to Figure 4.19**

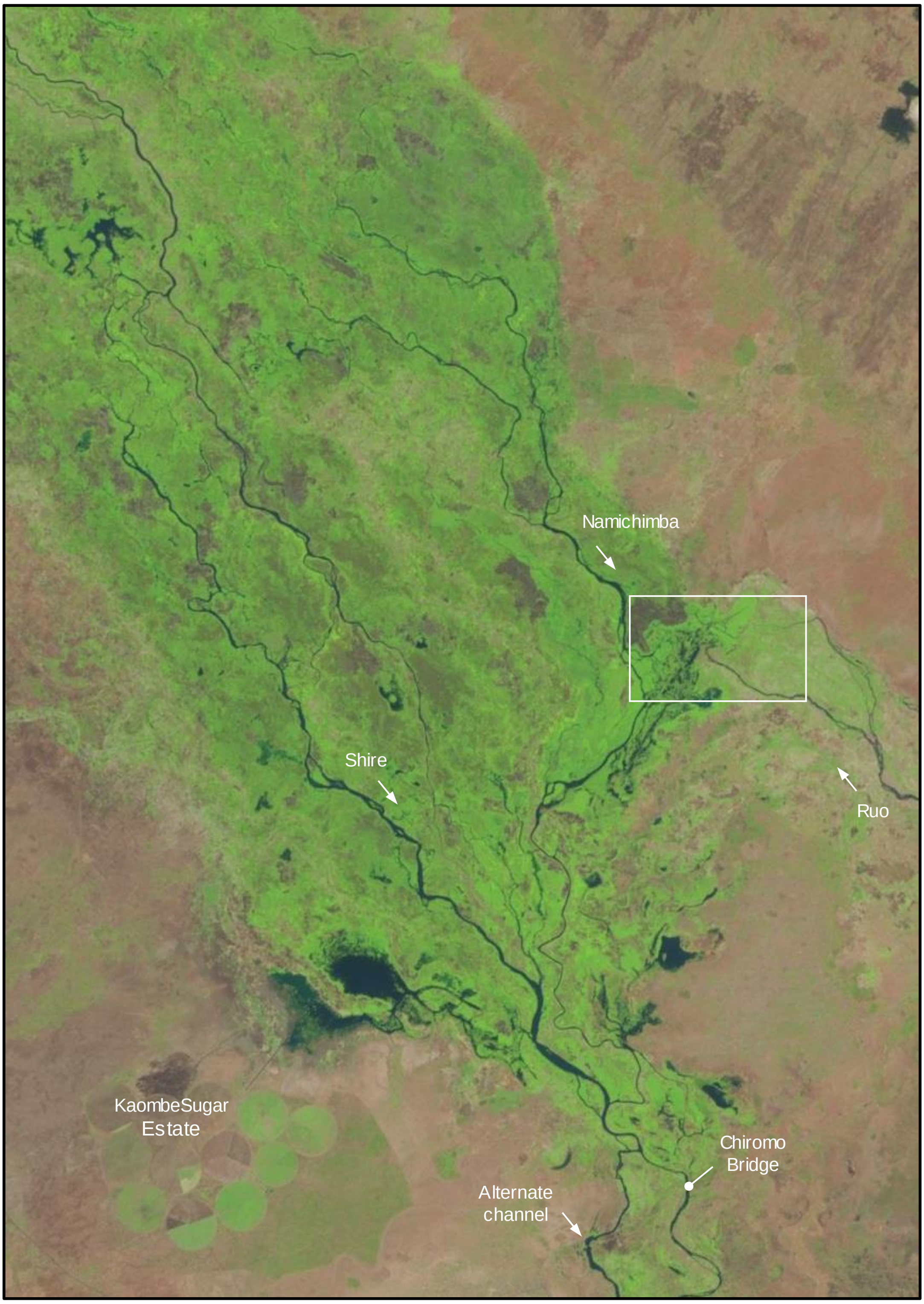

Figure 4.24 Sentinel-2A[243] (28 October 2016) image of the central/southern Marsh, showing the Ruo River's altered active channel course into Lake Tomaninjobi from the south-east, and the alternate Shire River channel; the rectangular area refers to the images in Figure 4.25

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[243] source: USGS EarthExplorer (http://earthexplorer.usgs.gov/)

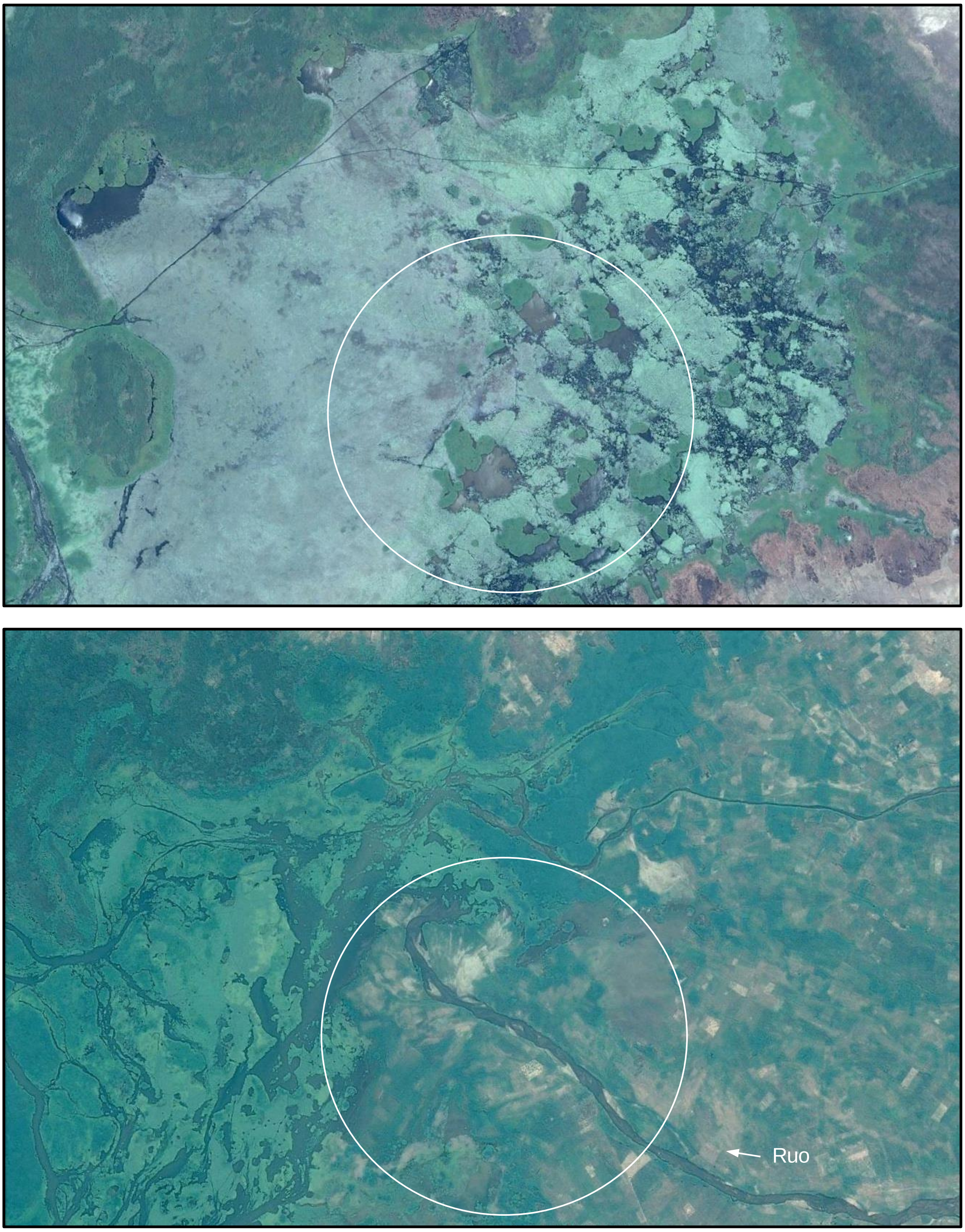

Figure 4.25 **High resolution satellite imagery (Google Earth) showing substantial diminution of the north-eastern extent of Lake Tomaninjobi due to sediment deposited by the Ruo River, following its re-routing through the Marsh in January; top: 27 December 2013; bottom: 27 September 2016; floating-leaved aquatic vegetation displays as white/pale-green; the spatial extent of the areas in this figure is indicated in Figure 4.24**

4.1.2 Flooding

The purpose of this component is to show how flooding patterns of the Marsh have changed over time using Landsat and other available imagery such as aerial photography, topographical and historical maps. As indicated in the previous section on channel change, there is very little imagery to show how inundation patterns have changed temporally:

- historical maps and literature (preceding the mid-20th century) make no reference to flooding extent;
- the two aerial photographs sourced are either of low resolution (1963) or for the dry season (1977);
- it is unwise to infer temporal changes in inundation from topographical maps, since they are based on aerial photography spanning a few decades, possibly from different (hydrological) seasons, and further confused by the masking effect of floating-leaved aquatic vegetation. For example, the southern lakes, which provide an indication of flooding, don't appear in the DoS 1:50 000-scale maps[244] (that are based on aerial photography between 1950 and 1977), but are expansive in the larger-scale 1:250 000 US aeronautical map (based on photography to 1965, Figure 4.8).

The Landsat archive, available through USGS EarthExplorer,[245] was reviewed for scenes covering the AOI, particularly during wet seasons. Explicably, the large majority of the available scenes were rendered unusable by extensive cloud-cover masking during flooding. Although this effectively thwarts the use of Landsat imagery for assessing temporal changes in inundation, a positive inference is that flooding is likely associated with high local[246] rainfall, and not only elevated flows from the upstream Shire. Extensive flooding, such as occurred in 2015, resulted from high regional rainfall, with the upstream Shire and the Marsh's adjacent (and downstream) catchments producing substantial runoff. An extracted image representing the only useful Landsat scene, capturing the March 2011 flooding of the Marsh (and downstream Shire), is presented in Figure 4.26. The image indicates runoff from the adjacent landscape; sediment-laden (lighter-blue)[247] flows from the Ruo River flowing into the south-eastern Marsh; and importantly, concerning the use of remote sensing for flood-mapping, the effective masking of inundation by emergent[248] and floating-leaved aquatic marsh vegetation. The hydrological modelling indicates that tributaries between Chikwawa and Chiromo (refer to Section 3.2.3) contribute substantial flow during episodes of marsh flooding.

Remote sensing using radar is useful where cloud cover masks optical (e.g., Landsat) imagery. Mapping of the January 2015 flood was done by the Centre for Satellite based Crisis Information (ZKI) of the German Aerospace Centre (DLR) using RADARSAT-2 (Figure 4.27). The product of this radar-derived mapping, given the cloud cover at that time, is remarkable, and was used to define the AOI for mapping and modelling purposes. Most of the central and eastern regions of the Marsh appear unflooded, however. These apparent 'gaps' correspond almost precisely with areas of dense and largely-indigenous marsh vegetation (i.e., papyrus, reeds and grasses). This is evident from the product of mapping landuse/vegetation types, which is presented in the next section (refer to Figure 4.28). It is fair to say that, irrespective of the satellite platform, emergent marsh vegetation in wetland environments presents a challenge for remote sensing of inundation patterns.

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244 Tomaninjobi Pool is labelled (but not Bangula) and small open-water surfaces are shown, hence the lakes may have been covered by floating aquatic vegetation, resulting in all areas collectively denoted as 'marsh'
245 http://earthexplorer.usgs.gov/
246 and regional
247 in the rendered image, brown in reality
248 emergent vegetation is inundated, but not submerged

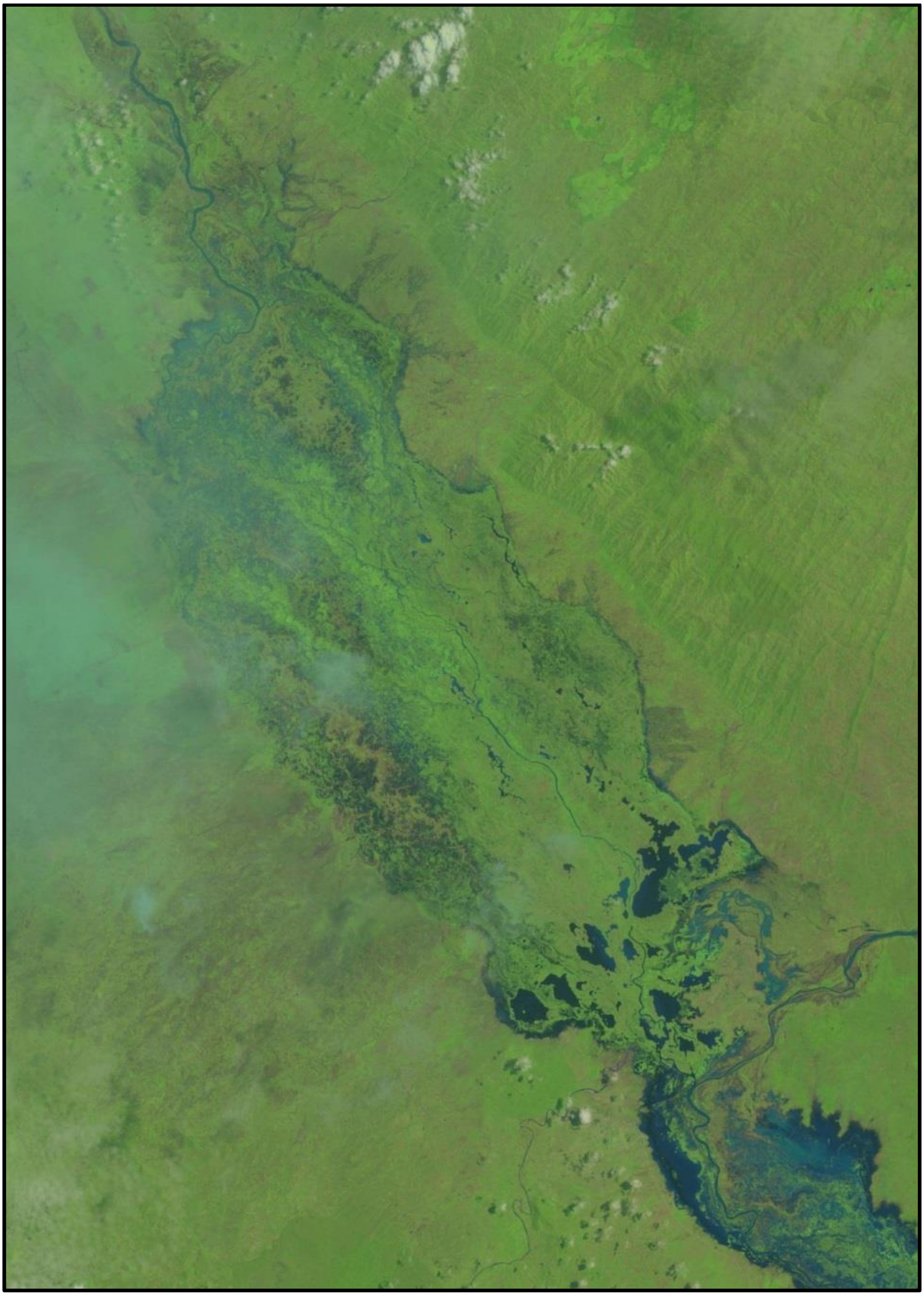

Figure 4.26 **Landsat LE7 'LandsatLook natural colour image' (4 March 2001) of the Elephant Marsh and downstream of Chiromo Bridge**

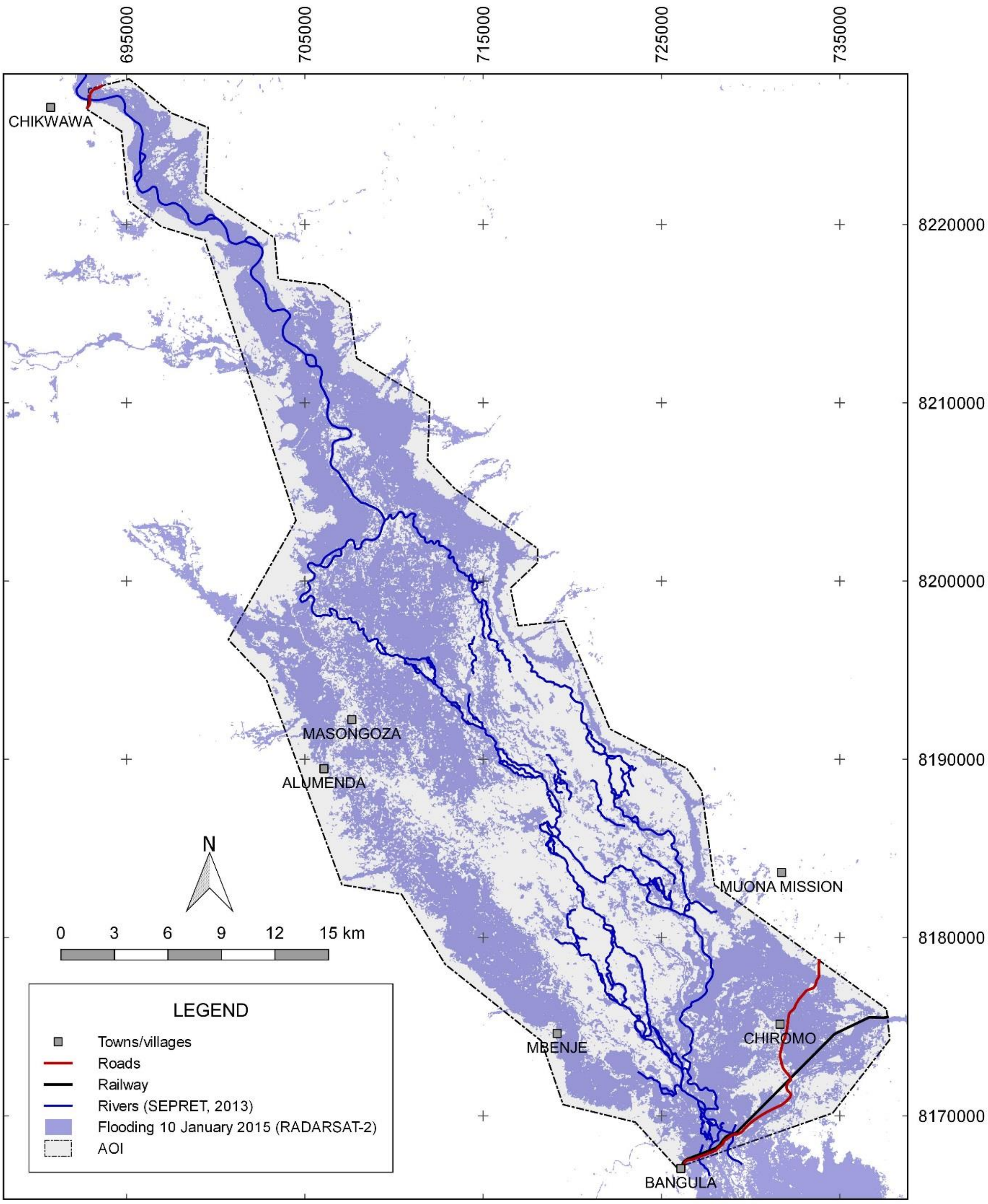

Figure 4.27 Flood extent in the Elephant Marsh on 10 January 2015, mapped by ZKI/DLR using RADARSAT-2; river channels digitised from SEPRET'S 2013 aerial photography; CRS is Arc 1950 (Malawi)

Simple, empirically-based methods involving correlated relationships based on measured data (e.g., discharge and floodplain inundation using remote sensing) have limited predictive capabilities (i.e., they are rather inflexible). This is because their application is generally restricted by both the number of variables and the value ranges upon which they are formulated. For the Elephant Marsh, flooding is a consequence of the combined effect of: upstream Shire River flows; adjacent tributary runoff (inflows); backup effects of the Ruo River combined with changes in flooding extent resulting from the breached embankment; and intercepted rainfall and evapotranspiration. Given this, and the uncertainties associated with many of the variables,[249] even with a good complement of historic remote sensing data (and neglecting inundation associated with emergent marsh vegetation),[250] it is doubtful, at best, that an empirical approach could be successfully developed that relates the above variables to extent of inundation. This directs attention to the inherently more complex and highly computational hydrodynamic modelling, which is described in Chapter 5.

Hydrodynamic modelling and other aspects of this study require an assessment of landuse and vegetation types and their spatial distribution in the Marsh, and this is dealt with in the next section.

4.2 Landuse and vegetation distributions

4.2.1 Mapping using remote sensing

For mapping landuse and vegetation distributions in the Marsh, various commercial and freely-available remote sensing images were considered. Landsat imagery at a spatial resolution of 30 m was deemed too coarse, and a resolution of ~5 m was considered necessary. Compatibility with the underlying (2013) DEM[251] also necessitated the use of imagery that pre-dated the 2015 flood.[252] Commercial products were therefore also investigated while recognising the trade-off between spectral/spatial resolution, and cost. SPOT 5[253] and RapidEye (RE) platforms were assessed, and the latter was selected.

The RE imagery is at a 5-m resolution (resampled from 6.5 m) and contains five bands: three visible, RedEdge (RE) and Near Infrared (NIR). The latter two are useful for vegetation studies. The wavelengths of these bands are given in Table 4.2. The imagery was obtained from Blackbridge.[254] Dates were sought towards the end of the dry season, to differentiate between permanent marsh and seasonal vegetation and because, at that time of the year, surface water is confined to permanent channels and lakes, and the scenes are generally cloud-free. The 22 November 2014 was selected, with six tiles covering the AOI between Chikwawa and Chiromo.

Classification (unsupervised and supervised) and object-based segmentation methods were investigated for categorising the different landuse and vegetation types. None of these classification methods were found to be adequate on their own, mainly because of the varied and complex mosaic of landcover in the Marsh. From visual appraisal of the RE spectral imagery, the following primary landcovers were identifiable:

- water surfaces: channels and lakes, both with variable turbidity;
- mixed water surfaces/floating-leaved aquatic vegetation;
- indigenous vegetation (papyrus,[255] reeds, grasses, etc.);
- cleared and cultivated lands that were previously disturbed but regenerating, and disturbed at the time of imaging and;
- burnt vegetation (some time previously as well as very recently).

[249] e.g., tributary flows - refer to Section 3.4.2.2
[250] which is illogical, given it represents the most important areas of the marsh
[251] described in Section 5.2.2.1
[252] The Sentinel-2A satellite's high resolution (10 m) optical (freely available) imagery may be adequate, but this satellite was only launched on 22 June 2015
[253] 5 m resolution, but re-sampled from 10 m
[254] using their on-line catalogue (EyeFind) to select a date
[255] which may be floating

Table 4.2 Wavelengths for the five RapidEye bands

Band	Description	Wavelength (nm)
1	Blue	440 - 510
2	Green	520 - 590
3	Red	630 - 685
4	RE	690 - 730
5	NIR	760 - 850

The burning of indigenous vegetation is prevalent in the Marsh, and is used mainly to clear areas for cultivation. During the (remote sensing) analyses, it became apparent that recently[256] and severely burnt vegetation presents a fundamental classification problem as it is indistinguishable from water surface, across all five bands. Remote-sensing experts at Blackbridge confirmed that this was a challenge, and the use of an additional and more recent scene, for May 2015, was investigated. The intention was to apply classification differences over the season (i.e., temporally) to assist with distinguishing between water and severe burns in the 2014 imagery. Unfortunately, other temporal changes (e.g., in channel courses and vegetation distributions), which are characteristic of a marsh environment particularly after large floods, means that it is difficult to use temporal changes (between scenes) to tease-out (from a single scene) what was water cover versus severely burnt vegetation. An alternative approach was therefore developed, based on a series of filters and the reflective characteristics of adjacent areas, detailed below.

The following four broad landcovers were classified, with sub-categories allowing for eight landuse/vegetation types:

1. open water surfaces [1];
2. mixed water and floating-leaved aquatic vegetation [2];
3. areas with moderate-to-high disturbance in the Marsh:
    a) barren lands (includes bare ground adjacent to the Marsh) [3],
    b) cultivated lands, sparse or recently (previous dry season) burnt vegetation [4],
    c) severely and recently burnt vegetation [5];
4. vegetation types:[257]
    a) typically indigenous vegetation with a minor-to-moderate disturbance, but also includes previously cultivated areas that were regenerating[258] [6],
    b) indigenous vegetation (typically reeds/grasses), but also includes regenerating indigenous vegetation subjected to previous disturbance (especially burning) [7], and
    c) typically undisturbed papyrus, but may include other vigorously growing indigenous vegetation [8].

A stepwise approach was developed to isolate different landcovers based on spectral signatures identified in the different bands, and assimilate them to form the final mosaic, as summarised below:

- Vegetation types: the commonly used Normalised Difference Vegetation Index[259] (NDVI) was effective in differentiating between different vegetation types, using the following thresholds:
    - [4]: $\text{NDVI} <= 0.17$
    - [6]: $0.17 < \text{NDVI} <= 0.25$

[256] ~2 months
[257] i.e., areas with low disturbance in the marsh
[258] as at 22 December 2014
[259] (NIR - Red)/(NIR + Red)

- [7]: $0.25 < \text{NDVI} <= 0.38$
- [8]: $\text{NDVI} > 0.38$
- Moderate to high disturbance:
  - [3]: threshold for Band 3 (Red) of 9 000[260]
  - [4]: NDVI above
  - [5]: refer to approach below
- Open water and recently burnt vegetation (i.e., [1] and [5]):
  - apply a broad mask using Band 4 (NIR) threshold of 5 000 to extract potential open water and recently burnt vegetation (this, however, includes areas of previous disturbance that have regenerated);
  - vectorise[261] and compute the NDVI (using NIR and RE bands), and apply the following three filters:
    - Filter 1:[262] if >= 2% (individual polygon) area has NDVI <= -0.09, then classified as water surface;
    - Filter 2:[263] if < 2% area has NDVI <= -0.09 or 10% area has DVI <= 0.15 then apply Filter 3;
    - Filter 3:[264] generate 15 m buffers around areas of water surface/burn from above, and compute averages of the Band 3 and Band 4 reflectance's for the buffer areas; Equation 4.1 then defines the condition applied to the buffer areas, to differentiate between water surface and burnt vegetation for the internal areas.[265]

$$NIR \geq 1.8\, Red$$

Equation 4.1

- Aquatic floating-leaved vegetation [2]: it was important to distinguish between floating-leaved aquatic versus rooted emergent (e.g., papyrus, reeds, grasses, etc.) vegetation. This is since aquatic vegetation is associated with water bodies, and floating-leaved aquatic plants cover large areas of lake surfaces, masking the water column below it in remote sensing imagery. Thus, they indicate different underlying morphologies (and habitats), which is particularly relevant to the hydrodynamic and DRIFT modelling. A means for differentiating between them, however, was not obvious. Bands 3 to 5 (i.e., Red, RE and NIR) were found to be most useful for indicating aquatic vegetation, and the index formulated in Equation 4.2 was used. This represents the difference between two variations of the Red Edge NDVI (e.g., Wu *et al.,* 2009; Sousa *et al.,* 2012), wherein RE may be substituted for either NIR or Red:

$$(NIR - RE)/(NIR + RE) - (RE - Red)/(RE + Red)$$

Equation 4.2

Indices from Equation 4.2 were normalised and values less than 0.49 were effective in defining mixed water/floating-leaved aquatic vegetation.[266]

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260 Superimposed on the NDVI categorisation
261 the GIS process of creating vectors (in this case polygons) from raster or cell/gridded data-formats
262 This first-level filter applies a stringent criterion for extracting water surfaces.
263 This second-level filter removes areas of previous disturbance that have regenerated.
264 Visual interpretation of the imagery indicated that severely and recently burnt vegetation was typically surrounded by disturbance.
265 Minimum areas of 100 m^2 were applied
266 Processing required gap-filling (=< 100 cells) and a minimum grid cluster was also used (100 cells) prior to grid vectorisation; potential water/vegetation areas that were co-incident with open water were selected (since the index from Equation 4.2 also classifies some vegetation areas that are non-perennial); a minimum area of 1 000 m^2 was applied.

The landcover distributions in the Elephant Marsh classified using RapidEye imagery (22 November 2014) are illustrated in Figure 4.28. The rendered image clearly shows that most of the indigenous marsh vegetation and lakes are distributed in the eastern/central/southern regions of the Marsh. This contrasts with the situation some 35-years ago, depicted in Figure 4.13 (left), when base flows were substantially higher, and the lakes in the southern region were extensive (white shading). The recent (i.e., 2014) situation more closely resembles that of 1999 (Figure 4.13, right).

The approach for discriminating between permanent marsh and seasonal vegetation was to use remote sensing imagery for the end of the dry season. There were two main difficulties with the classification:

- given the multispectral remote sensing data used, it was not possible to distinguish between irrigated sugar cane and marsh vegetation (particularly reeds and grasses).[267] This is evident in Figure 4.28, which shows the large sugar cane estates to the north-west of the Marsh. This also occurs, but to a lesser degree, along the floodplain upstream of the Shire/Namichimba split, and;
- it was not possible to distinguish between seasonal indigenous vegetation and dryland cultivation.

These issues were taken into consideration when the landcover classification was used, e.g., in the DRIFT assessment (Brown *et al*., 2016).

4.2.2 Ground-truthing

The AOI covers ~600 km^2 and large portions or the Marsh are practically inaccessible, which meant that ‘ground-truthing’, *per se*, was not a viable option for assessing the accuracy of the landcover classification, so an alternative and iterative method was used. This comprised the stepwise classification approach (outlined previously), and the formulation of indices and (their) threshold values, and involved a combination of ground- and aerial-truthing:

- ground-truthing data were collected during two field trips to the Marsh: one in the wet and one in the dry season of 2015. During which time ‘vegetation’ sites were identified and sampled (Figure 4.19) and the entire 95 km length of river between Chikwawa and Chiromo, including major lakes and selected distributary channels, were surveyed;
- aerial-truthing involved cross-referencing the classification using:
    - high resolution SEPRET (2013) aerial photography (e.g., Figure 4.20);
    - selected Google Earth (GE) imagery:
        - a GE image for 29 October 2014 (i.e., only 25 days preceding the RapidEye image) covers more than half the Marsh, and was particularly valuable for the landcover categorisation (e.g., Figure 4.29);
        - a large section of the Marsh (including the entire southern region) is covered by an image taken only a year earlier (9 November 2013).

[267] To differentiate between marsh vegetation and irrigated crops, hyperspectral data (providing numerous narrow bands over the continuous spectral range) would be required (e.g., Rosso *et al.,* 2005)

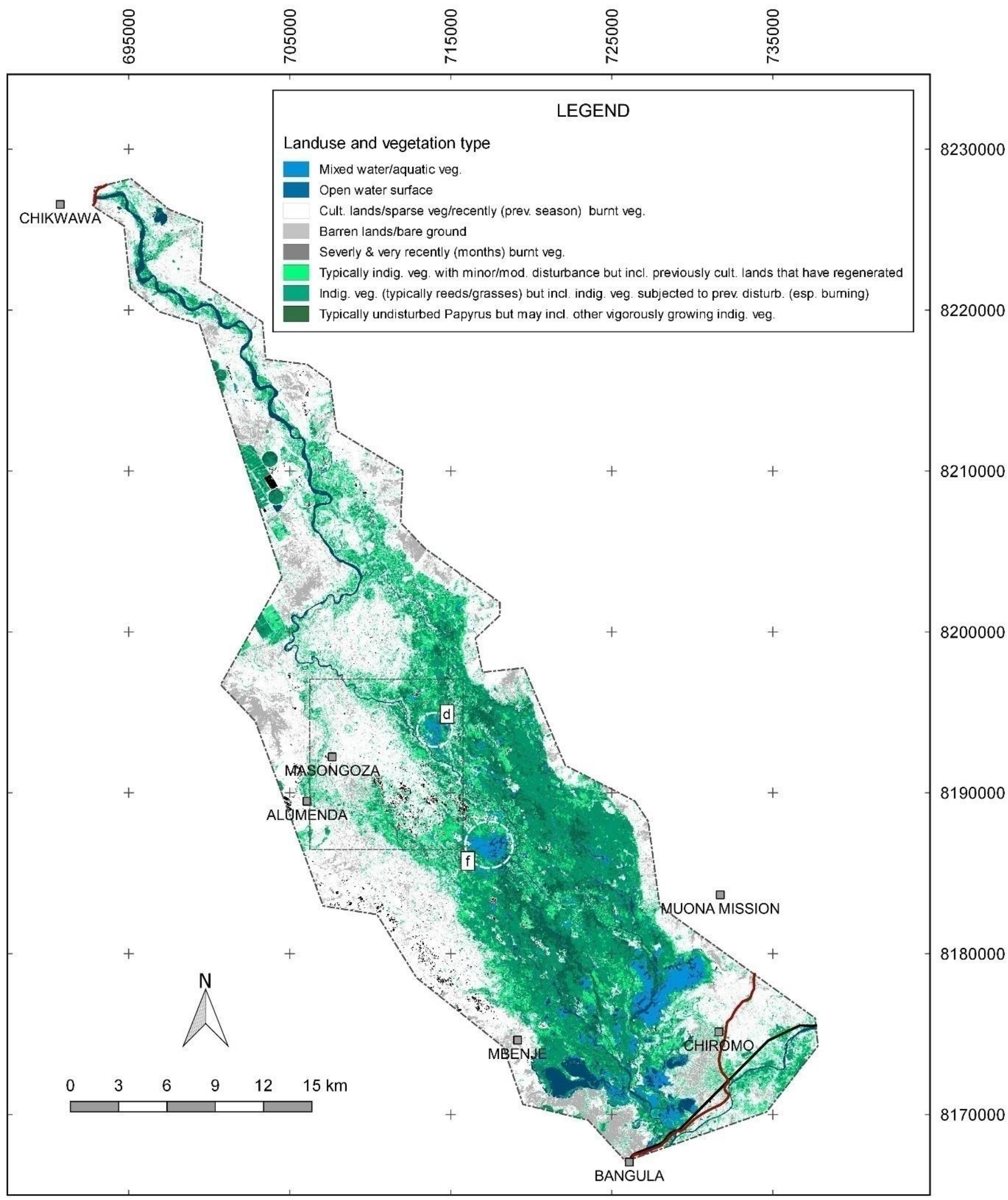

Figure 4.28 **Landuse and vegetation distributions in the Elephant Marsh, derived from RapidEye imagery from 22 December 2014; the rectangular inset refers to the higher resolution image in Figure 4.29; 'd' and 'f' indicate the positions of two shallow lakes, referred-to in Section 6.2.1; CRS is Arc 1950 (Malawi)**

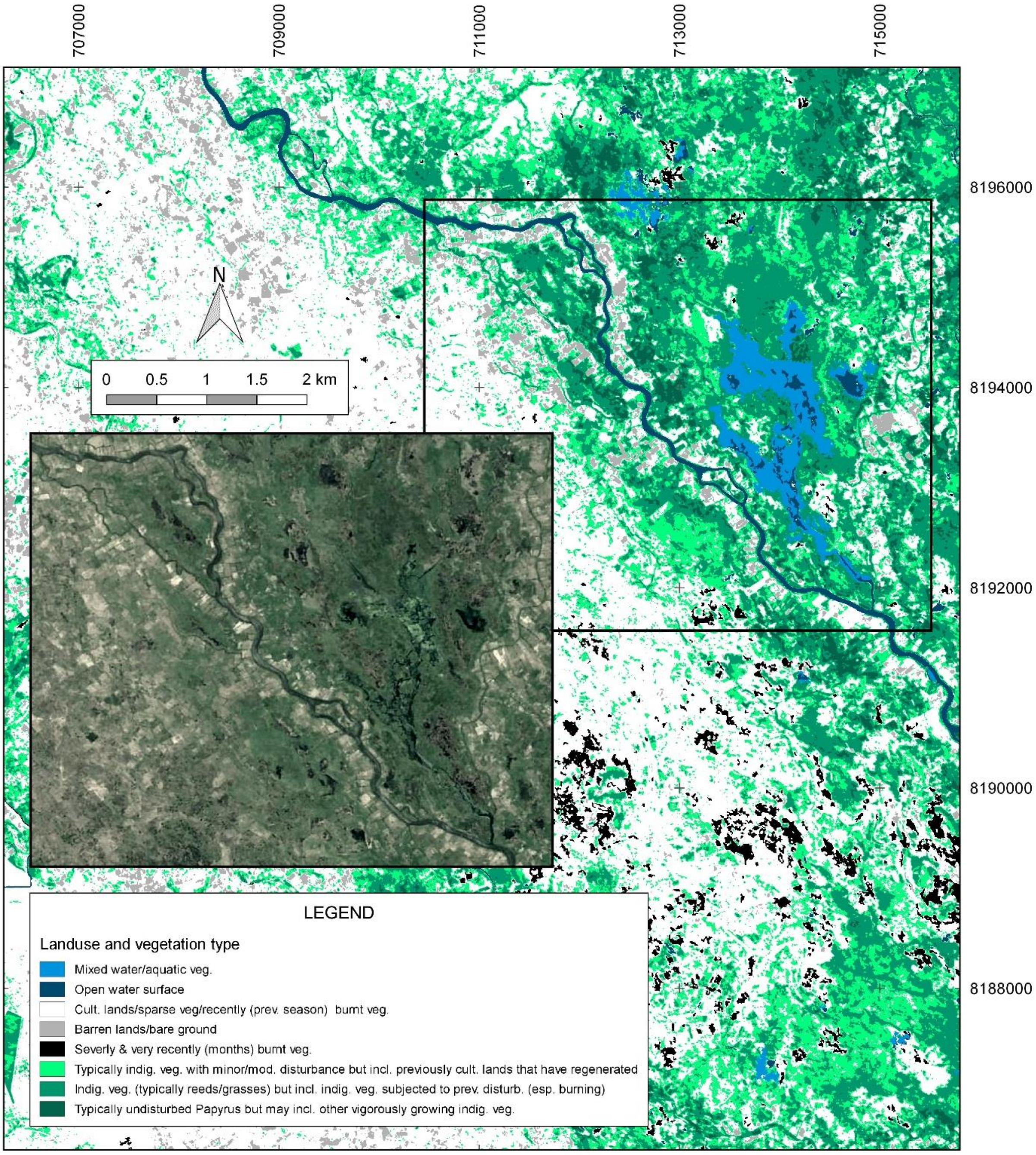

Figure 4.29 Landuse and vegetation distributions for a section of the Elephant Marsh, derived from RapidEye imagery from 29 October 2014; comparative GE image for 29 November 2014; note the disturbance along the channel margins; the area in this figure is indicated in Figure 4.28; CRS is Arc 1950 (Malawi)

5 Hydrodynamic modelling of the Marsh

The hydrodynamic modelling of the Elephant Marsh is described in five main sections, starting with the need for modelling, review of existing models, and approach used in this study; then existing and additional data collected in this study (hydrological, hydraulic and topographical); model development (or setup); model calibration, and lastly; model application, which includes hydrological scenarios, post-processing results for use in the DRIFT DSS and an assessment of the attenuation capacity of the Marsh.

5.1 Background and review

The purpose of this component of the hydromorphology sub-study was to develop a means for (quantitatively) linking the hydraulic behaviour of the Marsh to the hydrological regime. The water balance in the Marsh comprises flows into the marsh from the upstream Shire River; flows from local tributaries, including the influence of the Ruo River; rainfall falling directly on the Marsh and evapotranspiration. The water balance, in turn, provides the basis for considering how potential changes in the hydrological regime (arising from upstream flow regulation at Kamuzu Barrage and water abstraction) and/or anthropogenically-influenced climatic futures are likely to affect hydraulic habitat, both spatially and temporally.

Hydraulic habitat usually refers to ‘wetted’ components of habitat and does not account for the biota inhabiting that space. For the Marsh, however, the hydraulic habitat incorporates the landuse/vegetation types classified in the previous chapter, such as shallow lakes, indigenous marsh vegetation (e.g., papyrus and reeds), and areas subject to various levels of human disturbance ranging from cultivated to fallow and burnt areas.

Hydrodynamic analyses (or modelling) provide a means of quantitatively-linking hydraulic habitat to flow (or discharge). This is useful because biota respond to flow (or discharge) and its temporal characteristics through changes in local hydraulic conditions (e.g., depth, velocity and inundated area) in the many distributary channels flowing through the Marsh, along the channel margins, and across the adjacent floodplain/marsh landscape. The results of hydrodynamic modelling are particularly useful in holistic Environmental Flow assessments as they provide robust habitat-related indicators of hydrological change that can be linked directly to biotic response variables.

The development of a hydrodynamic model for the Elephant Marsh is a substantial task, and so before embarking on such, the suitability of existing models for use in this study was assessed.

5.1.1 Existing models

The Flood Risk Management Study of Atkins (2012) used a modelling framework (hydrological and hydraulic) to: construct and calibrate a hydrodynamic model of the catchment capable of “accurately” predicting inundation of the floodplain for extreme fluvial flooding; simulate floodplain inundation for a range of design flood scenarios; and produce flood maps of the catchment for a range of design modelling scenarios.

The spatial extent of the modelling was the length of the Shire River in Malawi, downstream of Liwonde Barrage. The hydrological component of the Atkins study involved rainfall-runoff modelling at a sub-daily time scale, with rainfall data obtained from 23 stations. The project’s data archive, kindly provided by Atkins,[268] did not contain any daily or sub-daily data, however, and it appears that the study used design hyetographs[269] for various return periods to generate synthetic discharge hydrographs, which while useful for the Flood Risk Management Study, could not be used here. The hydraulic component of the project used the linked 1-d/2-d Infoworks RS software for hydrodynamic computations. The SRTM[270] 90-m resolution DEM was used for the Marsh, with cross-sections surveyed for the Ruo River; the railway embankment, though incorporated in the model, was not surveyed.[271]

Atkins cited difficulties with topographical parametrisation of the hydraulic model using SRTM data. These difficulties stemmed from a combination of plan resolution, vertical (in)accuracy[272] and the fact that radar (used in the SRTM mission) does not penetrate water to provide bed elevations. No calibration results were included in the 2012 report to allow an assessment of the model's predictive accuracy. Licensing requirements for the Infoworks RS software aside, the model-setup was not available for this study, but in any case it appears that it is at too coarse a resolution to have been used. It was therefore necessary to develop a hydrodynamics model specifically for this project.

5.1.2 Modelling approach used in this study

Concomitant with advances in computing technology over the past three decades has been the development of multi-dimensional hydrodynamic models. For spatially extensive, topographically and hydraulically complex systems, such as the Elephant Marsh, a two-dimensional (2-d) model with advanced functionality is required. There are numerous 2-d hydraulic models that could be used for modelling the Marsh, including: MIKE 21; RMA2; RiverFlow2D; Infoworks, TUFLOW; Delft3D; BASEMENT and HECRAS 5. These models are commercial software, except the last two, which are freeware.[273] The high cost of these proprietary programs means that modellers usually have access to a specific model. Whichever model is used, it should be capable of accounting for the fundamental physical characteristics and processes. These include, *inter alia*, inflows at various time steps; complex topography and associated flow patterns; losses and various model boundary configurations, including, very importantly, large-scale wetting and drying of event and seasonally-inundated morphological features.

Of these and based on previous experience with modelling floodplain systems, RMA2 was selected for use in this study. It is a depth-averaged, 2-d model that uses finite elements and is based on implicit solutions of fully non-linear shallow water equations. It was developed by Norton *et al.* (1973) of Resource Management Associates, under contract with the USACE (Wurbs, 1994). The model has been extended over the past four decades, and a version (together with pre- (CFGEN) and post-processors which are part of the TABS[274] numerical modelling system) is maintained by the Waterways Experiment Station (WES) Hydraulics Laboratory (Donnel, 2011). A commercial version, with licensing, is also available from Resource Modelling Associates (King 2016), that includes ongoing updates. Pre- and post-processing software for RMA2 includes RMAGEN and RMAPLT, respectively.

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[268] Dan Wykeham, pers. com.
[269] distribution of rainfall over time
[270] The SRTM is an international research effort spearheaded by the US National Geospatial-Intelligence Agency (NGA) and the US National Aeronautics and Space Administration (NASA). It has obtained digital elevation models on a near-global scale from 56° S to 60° N to generate one of, if not, 'the' most complete high-resolution digital topographic database of Earth.
[271] its height was estimated
[272] SRTM DEM data is provided in 1 m elevation increments, but is not accurate to the nearest metre. An objective of the mission was to provide DEM data with at least 16 m absolute elevation accuracy at the 90% level.
[273] Freeware models generally have reduced or limited functionality as well as spatial constraints, although more (e.g., HECRAS v5) are been developed.
[274] acronym unknown

Multi-dimensional hydrodynamic models as needed for the Marsh are usually used to simulate hydraulic behaviour over short time-periods, such as hours or days; these generally being associated with isolated hydrological events. Since the hydrology of the Shire River has changed so much over the last few decades (Figure 3.8), hydrodynamic simulations for a long period was required for this study.

The capacity of RMA2 to simulate long-term hydraulic behaviour in complex systems was recently demonstrated for the Pongola River Floodplain in South Africa, which was successfully modelled by Birkhead (2014) using the King (2014) version of RMA2. The Pongola Floodplain comprises many seasonal and perennial pans that are periodically filled by water that overtops active channel levees. The Pongola simulations were for a 15-year period, and required run times of ~24 hours, which are reasonable considering the large size of the model setup[275] and rapidly varying flow conditions. The area of the Pongola Floodplain is about one-sixth that of the Marsh.

The RMA2 software offers the only known explicit simulation by a 2-d hydraulic model of so-called 'marshing' flow, which is used to characterise flow through submerged vegetation, by defining a transition depth of reducing porosity and potentially increasing flow resistance. Based on this, and previous experience with this software, it was an obvious choice for modelling the Elephant Marsh's hydrodynamics.

Even with the latest available topographic information (refer to Section 5.2.2.1) and the daily hydrometric data developed within this study (refer to Chapter 3), it was expected that 2-d hydrodynamic modelling would be challenging. This proved to be so. In the next section, the 'data' required to parameterise the hydrodynamics model are discussed.

5.2 Data

Essentially, three types of information are required to develop, calibrate and apply sophisticated hydrodynamic modelling approaches, such as RMA2. These are hydrological, hydraulic and topographical information.

5.2.1 Hydrological and hydraulic

The primary hydrological data required were daily discharge time-series of flows into the AOI between Chikwawa and Chiromo. These included the Shire River at Chikwawa and flows from the sub-catchments adjacent to the Marsh (both banks), which include the larger tributaries such as the Mwanza, Mwanphanzi, Maperera, Thangadzi (East and West), Nkombedzi Wa Fodya and many smaller streams (Figure 3.1 and Figure 4.6). In addition, it was necessary to include the Ruo (even prior to its 2015 course) because of its influence on the hydraulic behaviour of the southern region of the Marsh. Rainfall data were also necessary. Chapter 3 'Hydrology of the Marsh', describes the methods used to generate the hydrological time-series for the hydrodynamic modelling. The discharge time-series were based, as far as possible given the data issues mentioned in Chapter 3, on measured data. The reason being that it is preferable to develop and calibrate models on measured than modelled information as it reduces underlying uncertainties.

Hydraulic data for the Elephant Marsh are basically non-existent, comprising only gauge plate records at the Chiromo hydrometric station (1G1). As discussed in Section 3.2.1.4, hydraulic behaviour at the

[275] 22 470 elements

Chiromo Station was complex (pre-2015). Water levels at the bridge have responded to flows in both the Shire (flowing through the Marsh) and the Ruo, which joined the Shire a short distance downstream. Flow reversal occurred during periods when the Ruo flowed strongly relative to the Shire (e.g., Pike and Rimmington, 1965). In addition to this, the downstream Shire River has been subjected to sedimentation over many decades; evidence of this is presented in Chapter 6 which deals with sedimentation of the Marsh. Although the bridge structure at Chiromo presents a location for a hydrometric station from the point of accessibility and resilience,[276] hydraulically, it is a poor location. Therefore, although historic water levels at Chiromo were invaluable for developing an appreciation of sedimentation issues in this locality and for calibrating the hydrodynamics model, they needed to be used circumspectly. Water level records from the Chikwawa hydrometric station (1L12) were also most useful for indicating sedimentation trends, but for the modelling, a discharge rather than water level time-series was required at this upstream location.

The extent of flood inundation, derived from remote sensing data (e.g., Figure 4.26), can also be indirectly used to calibrate hydrodrodynamic models. For the Elephant Marsh, however, imagery using optical satellite platforms (e.g., Landsat) was largely unusable due to cloud cover, and radar platforms (e.g., RADARSAT, Figure 4.27) do not indicate flooding of inundated areas below vegetation (i.e., when vegetation is emergent).

5.2.2 Topographic

5.2.2.1 Existing data

Topographic data, in the form of a DEM, is fundamental for 2-d hydrodynamic modelling of floodplain/wetland environments. DEMs such as the global-scale SRTM, and more recently AW3D30[277] from the Advanced Land Observing Satellite through the Japan Aerospace Agency, are invaluable public domain resources. A higher-resolution 30 m version of the SRTM DEM was released after the Atkins (2012) study, and AW3D30 also covers the Marsh's AOI. Even so, the low resolution of these DEMs for use in hydrodynamic modelling of flat areas such as the Elephant Marsh is an issue.

Akins (2012) referred to an imminent Light Detection and Ranging (LiDAR) survey of the Shire River Floodplain, committed-to and funded by the World Bank. LiDAR produces topographical data of exceptional accuracy, and is the data of choice for hydrodynamic modelling of low relief environments. Conventional topographic LiDAR, however, is unable to penetrate water bodies (Smart *et al.*, 2009) and dense vegetation also presents a difficulty.[278]

During this study's inception phase it became apparent that a survey of the Marsh had been performed by SEPRET in 2013 and the data were obtained from the DoS in Lilongwe. The products of the survey include both orthophotos (at 0.6 m resolution) and the DEM is gridded at 2 m, both supplied as many tiles in TIFF[279] format. The tiles were mosaiced to produce a composite areal photographic image and DEM covering the AOI. The (SEPRET) DEM was developed photogrametrically,[280] which is not particularly suited to a survey of wetland-type environments: this technique produces a Digital

[276] particularly with respect to flood damage
[277] available for southern Africa, but has missing data
[278] In recent years, however, bathymetric LiDAR has become a proven a tool for the collection of both elevation and depth information, but depends on the clarity of the water: 2 to 3 times the Secchi depth (https://www.e-education.psu.edu/lidar/l2_p6.html). It is unlikely that even the bathymetric LiDAR will be able to penetrate through aquatic macrophytes.
[279] Tagged Image File Format
[280] the science of making measurements from photographs

Surface Model (DSM), i.e., top of vegetation,[281] and water surfaces present a problem, especially clear water bodies. The latter is evident in the DEM for the Marsh's channels, the elevations of which are variable and in regions are higher than the surrounding terrain; depths in Lake Tomaninjobi exceed 10 m in clear water areas, which is erroneous.[282] The reported residual errors between modelled elevations and Ground Control Points (GCPs) were within 0.20 m (SEPRET, 2014), but none of these GCPs points were in the Marsh (Appendix Figure A1). The accuracy of the DEM is considered inadequate for hydrodynamic modelling of the Marsh. The reasons for having selected photogrammetry to develop the DEM, rather than LiDAR as recommended by Atkins, are unknown, but may relate to the high costs of the latter. The SEPRET DEM is, however, the most accurate source of topographic data for the Marsh, and as stated in this study's inception report, "*If the Atkins model is not used, then a hydrodynamic model will be developed for the Elephant Marsh, parameterised using the most appropriate existing data*".

Another issue with the SEPRET DEM were two missing tiles (e.g., Figure 5.1). Numerous attempts to acquire these missing data were unsuccessful.[283] At a later stage during the study, data in the form of coarse contours (rather than the original gridded raster format) was obtained through a concurrent SRBMP project,[284] and these were used to infill the missing regions of the DEM. Unfortunately, these coincide with channel courses of the Shire and Namichimba, resulting in areas of lower accuracy in the model.

Although it was not anticipated that additional survey data would be collected for this study, this was necessitated by a complete lack of water depths for the main channels flowing through the marsh, the many distributary channels and the ecologically-important lakes. If left unaddressed this lack of data would have affected the success of the hydrodynamic modelling, with knock-on effects for other sub-studies using its results. Thus, given the importance of hydrodynamic modelling within the context of the project, additional data collection was considered essential and is described in the next section.

5.2.2.2 Additional data collection

A field trip took place in September/October 2015 to, *inter alia*, conduct water level and bathymetric surveys of the more extensive and permanent lakes; Shire River between Chikwawa and Chiromo, and distributaries within the Namichimba channel network.

An airboat was used to survey the lakes, but after its failure a conventional boat with an outboard engine was used for the channel surveys. Depth profiling across the lakes was a severe challenge because of dense mats of floating-leaved aquatic plants (Figure 5.3). A purpose-designed and manufactured attachment, clamped to the side of the airboat, was most effective in deflecting the vegetation (Figure 5.3), allowing depth penetration of the sonar signal from an attached transducer. The lakes were surveyed along pre-planned transects, and pre-mapped routes were navigated along the river channels, which were still difficult to follow at times.

[281] LiDAR would provide some penetration, especially if carried out during the dry season
[282] from a bathymetric study conducted in this study
[283] although lines of communication were initially fruitful
[284] Justin Saunders (GIS expert, SRBMP) to whom we are most grateful

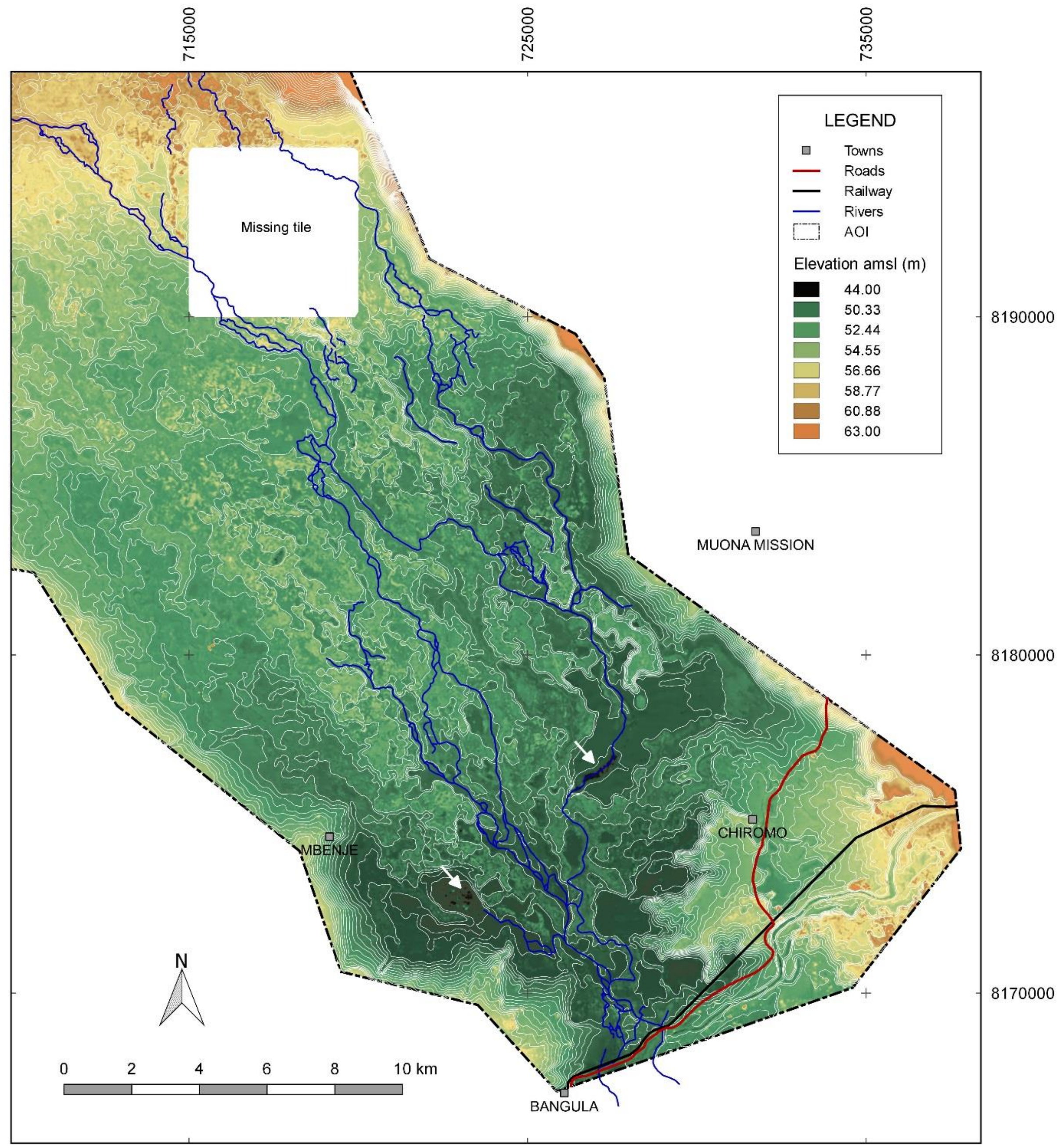

Figure 5.1 **SEPRET 2013 DEM, 0.5-m contours (white), and rivers digitised from the SEPRET orthophotographs for the lower section of the Marsh; one of the missing tiles is indicated; arrows indicate erroneous elevations (bed or water level) in the lakes; CRS is Arc 1950 (Malawi)**

Water-depth profiling was done using a Lowrance HD5 with on-board logging of (sub-second) records in sl2 format (Figure 5.3 left). The Lowrance HD5 outputs were converted to ASCII text format,[285] which included, position, depth and time-offset per record from start of logging.[286] The water levels in the

[285] using SonarViewer
[286] position is provided in using a custom Lowrance Mercator projected coordinate system; time-offset in milliseconds

lakes and distributary channels were surveyed using a Veripos LD7 DGPS with Apex[287] signal, which is a global high-accuracy positioning service with decimetre elevation accuracy. The unit provides a NMEA288 GGA string output *via* RS232 serial port, which was logged using HyperTerminal[289] (Figure 5.3 right). The NMEA GGA string includes a time stamp, position,[290] GPS data quality, orthometric height (mean sea level reference), and geoid separation.

Figure 5.2 Top: extensive coverage on the surface of a shallow lake by floating-leaved aquatic plants, making sonar surveys difficult; bottom: purpose-designed attachment fixed to the side of the airboat which was effective in parting dense mats of floating-leaved aquatic vegetation, allowing sonar pulses to penetrate the water depth

[287] Apex uses Precise Point Positioning (PPP) which is a global high-accuracy position technique. Corrections for satellites in the GPS constellation are derived real-time using Veripos's orbit and clock determination system (OCDIS).
[288] National Marine Electronics Association
[289] communication utility licensed to Microsoft Windows
[290] latitude and longitude (WGS84)

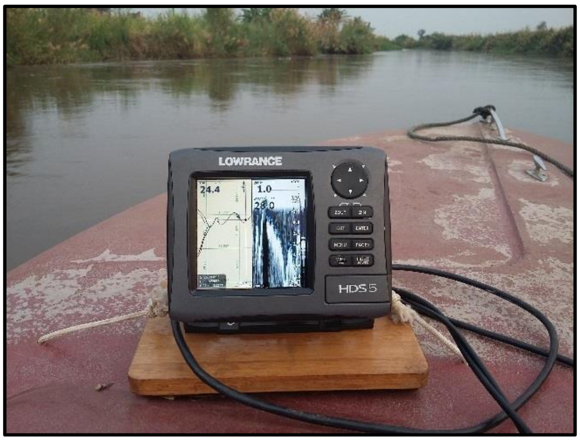

Figure 5.3 Bathymetric survey of the Shire River and Namichimba distributaries. Left: Lowrance HDS5 sonar equipment; right: Veripos LD7 DGPS connected to laptop for logging of the NMEA output string

A total length of ~130 km of river channels was surveyed, and ~55 km of transects were surveyed across the three biggest and deepest lakes, Bangula, Tomaninjobi and an unnamed lake between Tomaninjobi and Chiromo Bridge. Although they represent limited coverage of the Marsh with its many smaller lakes and distributary channels, the data obtained was nonetheless invaluable. To enable rapid and cost-effective surveys, two separate systems (*viz*. sonar and DGPS) were used. Considerable post-processing was therefore required to filter and merge the data sets, which necessitated the coding of bespoke software. The procedure was as follows:

- filter sonar records (extracting invalid depths), transforming the projected coordinate system (Lowrance Mercator) to geographical,[291] and merging data files and outputting records to the nearest second;
- filter DGPS records (extracting invalid positions), and merging data files, and;
- merge sonar and DGPS records using date/time and write records to the nearest second: the resultant file contained ~92 000 geographically positioned records of water surface elevation (amsl) and depths.

The use of these hydrological (daily time-series) and topographical (DEM and bathymetric) data, to develop the Marsh's hydrodynamic model, is described in the next section.

5.3 Model development

The development of a 2-d hydrodynamic model requires three essential components: First, the construction of a mesh consisting of elements; second, defining the physical characteristics of these elements (e.g., bed elevation, hydraulic variables) and; third, specifying boundary conditions (e.g., Shire River and tributary discharges; the railway embankment). A step-wise procedure was used that necessitated the coding of numerous procedures and algorithms to automate the development of the mesh, and linking the characteristics of mesh elements to the landuse/vegetation classification described earlier (Section 4.2).

[291] latitude and longitude (WGS84)

5.3.1 Finite element mesh

The mesh was first developed for the network of river channels, and then for the adjacent floodplain/marsh areas. Extensive use was made of Geographical Information System (GIS) software, namely public domain SAGA GIS and Quantum GIS (QGIS).[292]

The channel centre-lines were digitised from the SEPRET (2013) mosaiced orthophotograph covering the AOI, as this is the latest high-resolution image, and corresponds to the DEM used in the modelling. The traced river courses were smoothed, as 'gentle' transitions between adjacent (longitudinal) elements are desirable in the numerical modelling. Other (GIS) shape files and associated attribute tables were created using transects to define channel widths, and the physical characteristics of channel junctions (e.g., connecting channels; divergent/convergent and left/right bank junctions). Forty-three channels were incorporated in the model, with 54 junctions. The channel characteristics described above, captured in GIS using shape files and attribute tables, were written to plain-text file formats.

Software was developed to read this information and to automatically construct the channel mesh using quadrilateral elements. The size-proportions of, and between, adjacent elements, is an important consideration in 2-d mesh design. A few other variables influenced automatic mesh generation, and included element slenderness ratio; ratio of bank width-to-height; minimum and maximum bank heights; and maximum bank slope. Two-dimensional meshes are made up of elements, and three or more elements join to form nodes. Nodes require elevations, and for the channel bed nodes, these were obtained from the results of the bathymetric survey (described in the previous section). The channel mesh was written to file in .rm1 format,[293] and loaded in RMAGEN to check the mesh quality during its development.

The edge of the hydraulically-modelled area (within the broader AOI) was defined using flood contours from the 2015 flood event (Figure 4.27). The floodplain/marsh areas were meshed in QGIS using the Triangle software developed by Shewchuk (undated), available as the Basemesh Plugin (Vetsch *et al.* 2014). The software produces conforming Delaunay triangles, with (external) boundaries used to define the modelled area, and (internal) boundaries delineate features such as lakes (refer to Figure 5.4). Other features of the software include the use of breaklines to align mesh segments; conforming vertices (or nodes, called Steiner points); and restrictions on maximum element area. The Basemesh software provides outputs as shapefiles and text file format.

Purpose-coded software was then used to merge the quadrilateral elements forming the channel bed and banks, with the floodplain/marsh triangulation from the QGIS-Basemesh (Triangle) programs. This bespoke software also assigned elevations to all nodes in the triangular mesh based on the SEPRET DEM, which was processed as follows:

- bathymetrically surveyed lake areas were merged into the DEM, and;
- the 2 m-gridded DEM was re-sampled to 50 m.

Finally, the finite-element mesh was written in .rm1 format and loaded into RMAGEN for RMA2 pre-processing. The final mesh comprises 52 879 elements and 49 386 nodes.

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[292] QGIS: http://www.qgis.com; SAGA-GIS: http://www.saga-gis.org/en/index.html
[293] plain text file

5.3.2 Hydraulic properties

In RMA2, elements are assigned a 'type', which defines their hydraulic properties, and include flow resistance, turbulence behaviour and 'marshing' parameters. The marshing feature assists with the modelling of wetting and drying of intermittently inundated areas (i.e., non-perennial), and is central to the use of this model for characterising the hydraulic behaviour of wetland-type environments. Using this feature, when water levels fall close to the ground surface, they are confined within a vertical zone of low porosity and potentially high flow-resistance. This is particularly useful for modelling flows through emergent marsh vegetation, such as papyrus and reeds.

For the floodplain and marsh areas, element types were provided from the classification of landuse and vegetation types, described in Section 4.2 and illustrated in Figure 4.28. Since the classification cover was at a much finer resolution than the hydraulic analysis (i.e., at 5 m grids cf. size of the elements in Figure 5.4), a filter was used to compute the majority-type for each element. Similar covers (from a hydraulic perspective) were combined, and the types used were:

- channel beds;
- channel banks;
- open water surfaces, including areas with floating-leaved aquatic plants, i.e., [1] and [2];[294]
- disturbed areas (including bare ground, barren lands, cultivated lands and burnt vegetation, i.e., [3], [4] and [5];
- typically indigenous vegetation with a minor-to-moderate disturbance, but also including previously cultivated areas that were regenerating [6];
- indigenous vegetation (typically reeds/grasses), but also including regenerating indigenous vegetation subjected to previous disturbance, especially burning [7], and;
- typically undisturbed papyrus, but may include other vigorously growing indigenous vegetation [8].

5.3.3 Boundary and initial conditions

The boundary conditions used in the Marsh model include:

- daily discharge time-series at the upstream Shire River boundary (at Chikwawa);
- rating (or stage-discharge) relationships immediately downstream of the Shire-Ruo confluence, and at the breached embankment through which the alternate Shire channel flows;
- daily discharge time-series at the upstream Ruo River boundary;
- daily discharge time-series from 12 tributaries[295] flowing into the modelled area, and;
- daily rainfall falling on, and evapotranspiration from, the modelled area.

The elevation difference over the modelled area is ~30 m, and the slope adjustment method in RMA2 was used to compute an initial (restart) condition, from which transient (unsteady) simulations commenced.

[294] This was further sub-divided into two: lakes with bathymetric surveys (i.e., accurate bed elevations), and the balance.
[295] some smaller tributaries were combined to give a single inflow per sub-catchment (refer to Figure 3.1).

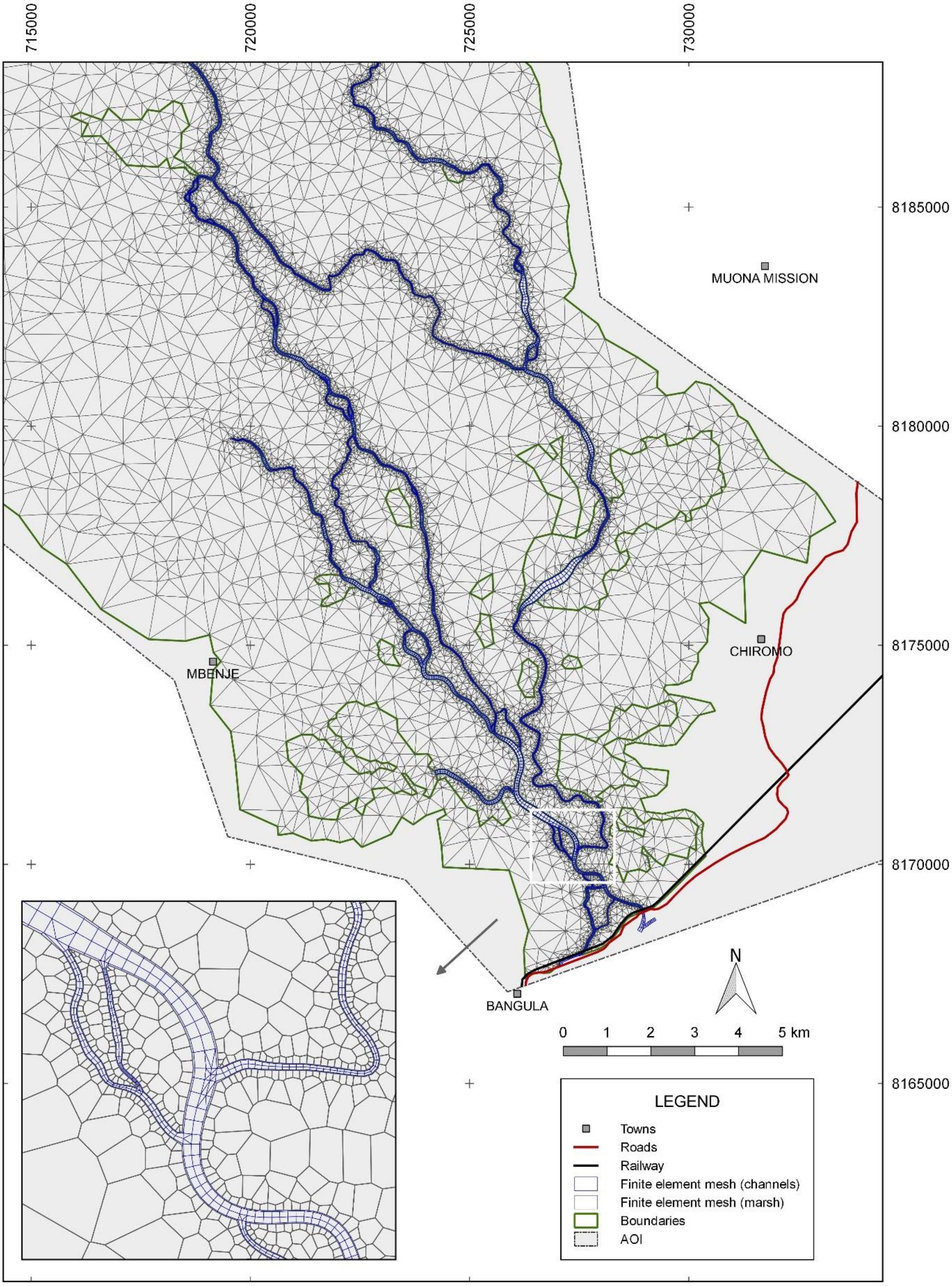

Figure 5.4 **RMA2 finite element mesh for the lower section of the Marsh, showing the distributary channels, external (model) and internal (lake) boundaries; CRS is Arc 1950 (Malawi)**

5.4 Model calibration

5.4.1 Description and results of the calibration process

The model was calibrated using the surveyed water surface profile between Chikwawa and Chiromo (Figure 5.6) and historic stage records from Chiromo Bridge (Station 1G1). As mentioned previously (Section 5.2.1), stage records at Chiromo need to be used circumspectly, due to influences of Ruo River flows, sedimentation, and the breached railway embankment; the effects of which on Chiromo's water level have changed temporally. Evidence of this is indicted by the scatter in the rating data plot of Figure 3.2 (bottom-right), which includes data for the period 1979 to 1998.

There are no recent stage-discharge measurements on which to develop rating relationships for the Shire-Ruo confluence, nor the alternate Shire channel through the breach. For this reason, it was necessary to estimate these downstream rating relationships as part of the calibration process. To do this, Equation 3.1 was fitted to the historic (1979 to 1998) rating data for 1G1, with $b = 0$ (Figure 5.5). A stage-gauge (level) offset was then applied to this 'functional' relationship, to reflect subsequent changes in the rating for the reasons given above (i.e., sedimentation, etc.). The hydrodynamic model was then used, iteratively,[296] to determine the flows in each of the Shire channels (i.e., at Chiromo Bridge and Bangula Breach). In this way, rating relationships were formulated representing approximate existing boundary conditions. The arrows in Figure 5.5 indicate rating points corresponding to conditions at the time of the 2015 field survey.

For each of the seven element types in the model (listed in Section 5.3.2), parameter values for the following variables were also determined as part of the calibration process:

- flow resistance and its depth-dependence;
- turbulence parameters, and;
- marshing parameters.

Plots of the surveyed (refer to Section 5.2.2.2) and modelled water surface profiles between Chikwawa and Chiromo, including a short (~7 km) stretch of the upper Namichimba and the most-downstream[297] (~15 km) stretch of the lower Namichimba, are illustrated in Figure 5.6. These are for a discharge of ~190 m^3/s at the time of the survey, at the end of September 2015. Overall, the profiles compare reasonably well, with average errors of -0.34 and -0.25 m for the Shire River upstream and downstream of the Namichimba split, respectively. Expressed in term of depth, the errors (average absolute) are 18 and 15%, respectively.

Time-series plots of recorded water levels (i.e., gauge plate - local datum) and modelled stage (relative to msl) are illustrated in Figure 5.7 for the Chikwawa (1G1) and Chiromo (1L12) Stations. Thus, recorded and modelled water levels are relative to different elevation datums.

[296] since it requires the downstream rating relationship, which is being determined
[297] i.e., upstream of its confluence with the Shire

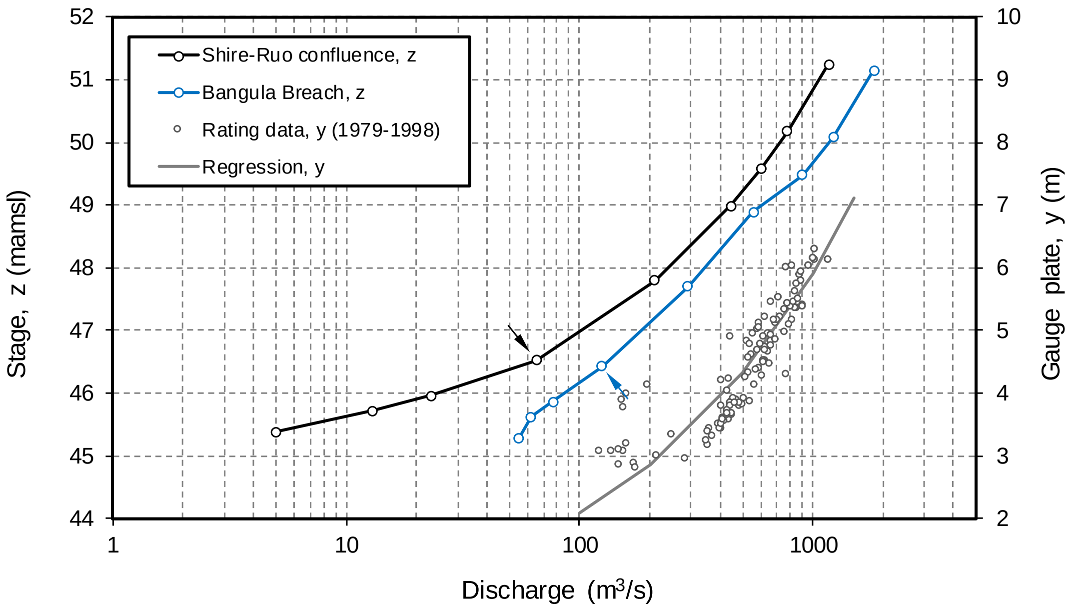

Figure 5.5 **Downstream estimated rating relationships for the Shire-Ruo confluence, and at the breached railway embankment near Bangula; arrows indicate points corresponding to the September/October field trip (Shire River discharge ~190 m³/s)**

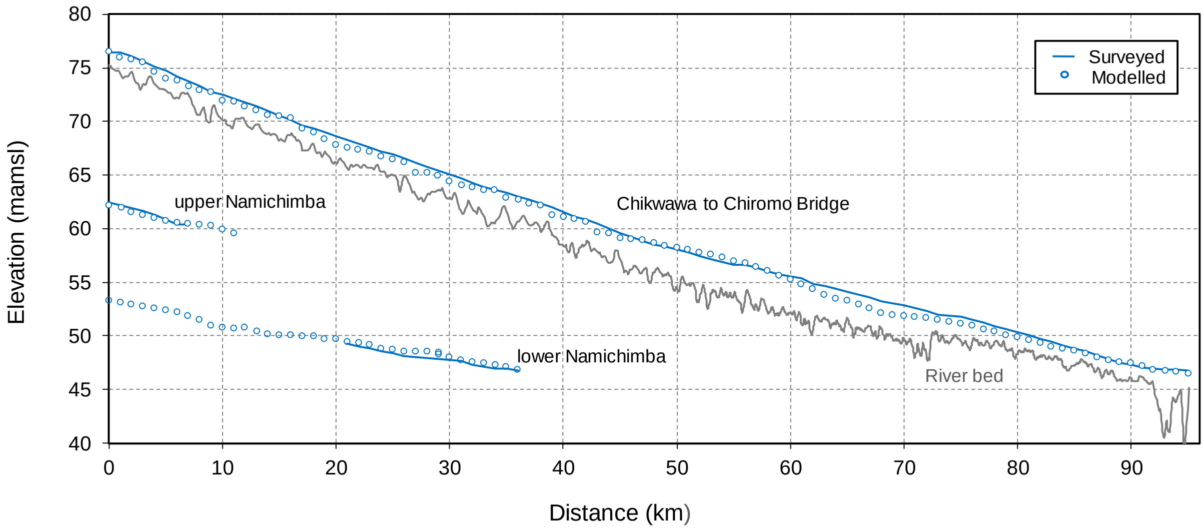

Figure 5.6 **Surveyed and modelled water surface profiles between Chikwawa and Chiromo Bridges, the upper and lower Namichimba (Shire River discharge ~190 m³/s)**

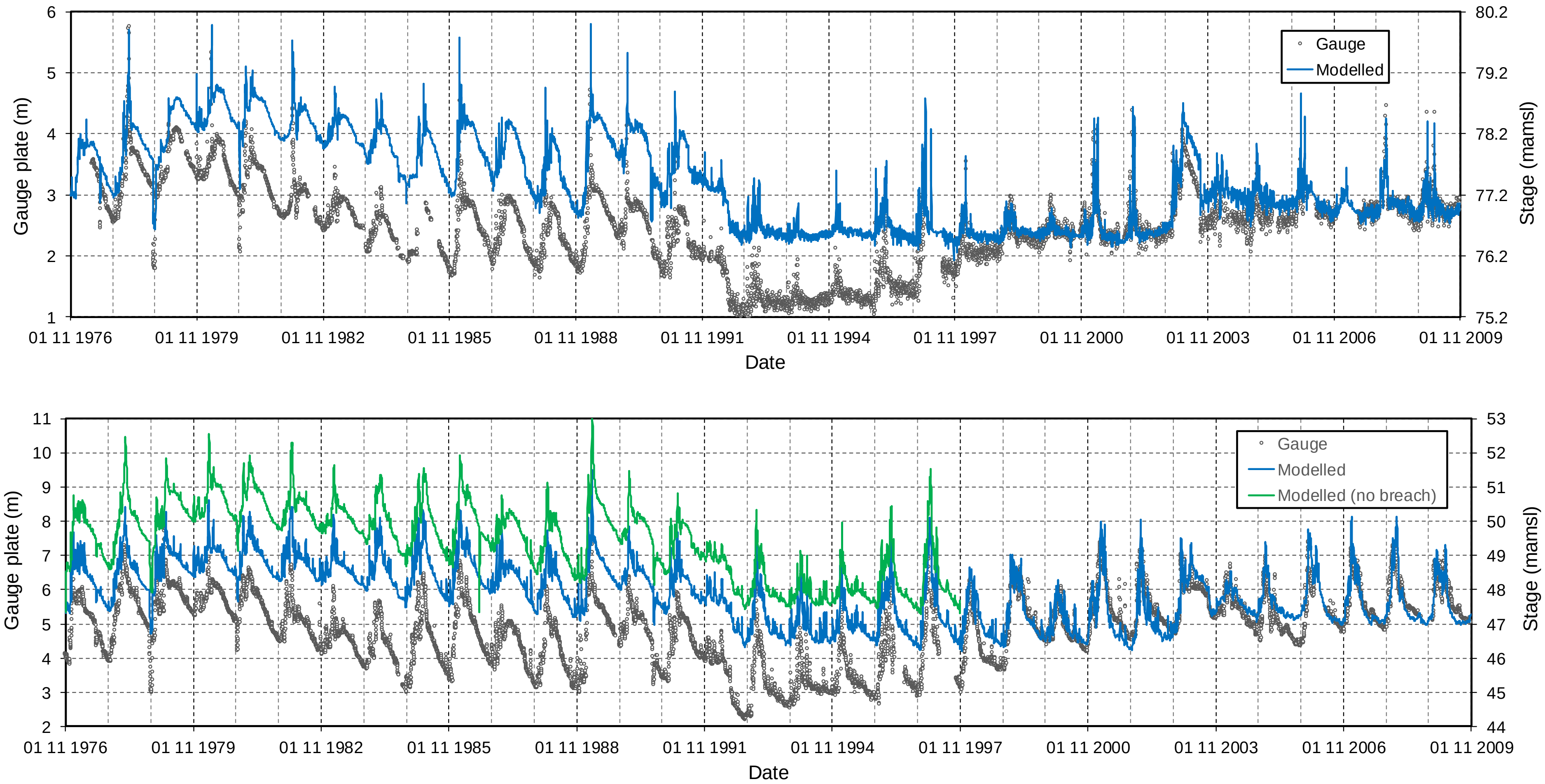

Figure 5.7 Gauge plate records and modelled stage time-series for the 33-year period 1976 to 2009 at Chikwawa (top) and Chiromo (bottom) bridges

Station history[298] information for Chiromo refers to a gauge plate datum of 42.0 mamsl, and this offset was used to align the vertical axes in Figure 5.7 (bottom).[299] Given that the physical template in the hydrodynamic modelling represents existing or at least recent (i.e., as provided by the DEM, bathymetric survey and downstream rating relationships), it is reassuring to note that a good correspondence between observed and modelled water levels has been achieved for the last decade or so, although less-so for some years within this period (i.e., low flows in 2001/2002; 2004/5). Prior to this, there are large differences due to temporal changes in the hydraulic controls on water level (i.e., sedimentation and the effect of the breached embankment).[300] It stands to reason that the breach has reduced water levels at Chiromo Bridge. A simulation was conducted to quantity this, using the existing topographical template (i.e., DEM) and no flow through the existing breach. A ‘no breach’ time-series is also plotted in Figure 5.7, and indicates that the breach has lowered water levels by ~1 to 1.5 m (i.e., the differences between the plots for the existing template and ‘no breach’ situation). These comparative water levels (*viz*. observed, modelled - existing template, and modelled - ‘no breach’) are useful, as they isolate changes in water levels at Chiromo Bridge due to sedimentation (i.e., the hydraulic effect of the breach has been accounted for). Figure 5.7 (bottom) indicates aggradation of up to about 4 m from about the 1980s. This is considered further in the next chapter (Section 6.2.3.1), which deals with sedimentation in the southern region of the Marsh.

For the Chikwawa Station, the gauge plate datum could not be sourced. Based on the comparative plots at Chiromo, it is reasonable to expect that modelled levels over the past decade or so should agree reasonably well with concomitant gauge records, and an offset of 74.2 m was applied in Figure 5.7 (top). Differences between time-series indicate the same trends as at Chiromo, but with less sedimentation since the 1980s, to the order of ~1.5 m. The comparative plots show that the bed level in 1976 was only marginally lower than in 2009: bed lowering occurred over the relatively high-flow period of the first 5 years, and subsequently, sediment accumulation occurred during the low-flow period of the 1990s.

The results of model calibration, indicated by these comparative plots using recorded water levels and modelled stages, clarify the large amount of scatter in the rating plots for the hydrometric stations at Chikwawa and Chiromo (provided in the hydrology chapter, Figure 3.2).[301] In the morphologically dynamic lower Shire River, the mistake of applying time-independent rating functions to compute discharge time-series from observed water levels (from hydrometric stations), is made evident.

Flow resistance values (Manning’s n) used in the model varied from: 0.030 for the river channel; to 0.050 for the channel banks and disturbed areas of the floodplain (i.e., ranging from bare ground to cultivated lands); to 0.150 for the most-dense indigenous marsh vegetation (i.e., reeds and papyrus). These values increased with reducing depths, up to 2 times. The extent to which the hydrodynamic modelling was required to simulate episodic wetting and drying of an extensive floodplain is illustrated by the five-fold range in inundation modelled within the period 1976 to 2009: ranging from 113[302] to 559 km^2 (excluding channels).

The RMA2 model was found to run efficiently given its large size (52 879 mesh elements), and a 33-year simulation took about the same number of run-time hours.[303] Simulations were done in batches of decades, using restart files for initial conditions at the start of the next batch. The default time-step used in the simulations was 12 hours, which is targeted at the dry season when changes are gradual.

[298] Atkins 2012 data archive
[299] i.e., 44 m on right axis = 2 m on left axis
[300] over the course of the 1990s, but extensive in 1997
[301] measurement errors aside
[302] of this, 70 km is made up of open water surfaces/lakes which may be covered with floating-leaved aquatic plants
[303] i.e., one hour’s run-time per year

Variable time-steps (down to 1 minute) were permitted when convergence was not achieved within 10 iterations.

5.4.2 Model refinement

Refinements to the Marsh hydrodynamic model would require improved data:

- 2-d modelling of topographically and hydraulically complex floodplain/wetland system, such as the Marsh, requires an accurate DEM. Although used in this study, the accuracy of the (SEPRET) DEM is inadequate for modelling the Marsh. A LiDAR survey, as recommended by Atkins (2012) and committed-to and funded by the World Bank would be the method of choice for any future topographical surveys of the Lower Shire Valley;
- further bathymetric surveys of lakes and distributary channels (as done for this study);
- reestablishment of the local hydrometric network, with specific reference to stage and rating measurements along the Shire River at Chikwawa, Chiromo and Bangula,[304] the Ruo River, and the larger tributaries flowing into the AOI (i.e., the Mwanza, Mwamphanzi and Maperera, and at least one of the tributaries flowing from the south/south-west, e.g., Thangadzi West or Nkombedzi Wa Fodya). Rainfall data have proven invaluable in this study for synthesizing discharge time-series where hydrometric data were inadequate, and future monitoring of precipitation should accompany (any) potential restoration of the hydrometric network;
- monitored stage fluctuations in the Marsh, particularly during wet seasons, would improve calibration. This could be achieved by using temporary (inexpensive) loggers, although securing them and ensuring their longevity would be difficult.

5.5 Model application

The process of developing and calibrating the hydrodynamic model has provided insights to many aspects of the Marsh's hydromorphology. Its main purpose, however, was to quantitatively link hydraulic behaviour to the hydrological regime to allow for the assessment of the effects of different hydrological regimes (or scenarios) on the Marsh's ecological condition (refer to Brown *et al.* 2016).

5.5.1 Hydrological scenarios

Hydrological scenarios, derived from two 33-year flow regimes, were considered: the historical measurement-based flow regime at Chikwawa described in the hydrology chapter (illustrated in Figure 3.8) and used to calibrate the hydrodynamic model; and a potential future flow regime representing maximum development of the water resource which includes the effects of climate change. Two other flow regimes were also developed: naturalised, which is largely of academic value as a scenario, since flows have been manipulated since barrage construction in 1965; and the 'present level of development', which represents a less-severe condition than the 'maximum development' scenario. Consequently, these two (additional) scenarios are not considered further in this nor were they considered in the related DRIFT sub-study (Brown *et al.* 2016).

[304] alternate right-bank Shire channel

The 'maximum development and climate change' scenario is described as follows:[305]
"*It has climate change impacts (A2 carbon emission scenario),[306] and medium upstream development. It also includes the Shire Valley Irrigation Project, higher water demand due to population growth, and two new hydropower developments (Mpatamanga and Kholombidzo).*"

This and other scenarios were obtained from the Basin Planning Framework Project (Niras/DHI, in prep.). While convenient and contributing to the integration of projects within the SRBMP, a challenge was the different time-scales: monthly scenarios versus daily in this study. Since flows in the Shire River are largely regulated at Kamumzu Barrage, a simple monthly-disaggregation of Shire River flows is inappropriate. The approach adopted in this study was to:

1. calculate monthly catchment contributions between Liwonde and Chikwawa for the scenario and naturalised conditions;
2. calculate differences between the scenario and naturalised time-series in 1. above, which approximately reflects water resource developments and the effects of climate change on flows in the sub-catchment between Liwonde and Chikwawa;
3. add 2. (above) to the scenario time-series (monthly) as modelled at Liwonde, and;
4. add 3. (above) to the daily time-series (from this study - see below) for the sub-catchment between Liwonde and Chikwawa,

The daily time-series (4. above) was modelled using the Antecedent Precipitation Index (API) described in Chapter 3 (Section 3.4.2), with rainfall data aggregated using stations from the upstream sub-catchment (Figure 3.1). The parameter values in Equation 3.3 (i.e. k and P_t) were calibrated using the difference between the measurement-based time-series at Liwonde and Chikwawa (described in Section 3.4.1; plotted in Figure 3.8).[307] The discharge time-series at Chikwawa for the 'maximum development and climate change' scenario is plotted in Figure 5.8. Also plotted is the historical (measurement-based) flow sequence used to calibrate the hydrodynamic model (i.e., as illustrated in Figure 3.8).

5.5.2 Post-processing hydrodynamic modelling results for use in the DRIFT DSS

The 'standard' output from a RMA2 simulation is a binary results file that can be loaded into RMAPLT for graphical displays and limited post-processing. The large spatial extent of the Marsh and length of record simulated meant that it was necessary to develop software for post-processing results required for further analyses in the DRIFT DSS. A plain text results file for selected nodes can be specified in the run (.rm2) file (e.g., Birkhead 2014), but the large number of nodes in the Marsh model (*viz*. 49 386) meant that this was not a viable option. Additional software was coded for this study by one of the original RMA2 developers, Dr Ian King, and allows for the extraction of water elevation and velocity results (for any number of specified nodes) from the binary output file, into a binary or to a plain text file.

Post-processing hydrodynamic modelling results required the selection of DRIFT focus areas or sites. Five sites covering the modelled area were selected based on vegetation type, hydromorphological influences, stage of transformation by cultivation, and priorities for fishing and/or harvesting of natural materials (Figure 5.9). For these sites, coverages by the different landuse or vegetation types are given in Table 5.1. Within each of these sites, hydraulic characteristics are discretely represented at nodes (from the finite element mesh), and it is necessary to divide the marsh into Voronoi cells (or

[305] Kevin Greaves (DHI), pers.com.
[306] refer to Section 3.5.1
[307] i.e., the daily flows from the Liwonde-Chikwawa sub-catchment

the more commonly known Thiessen polygons) - signifying the surrounding area represented by each node (Figure 5.10).

Table 5.1 Coverages by the different landuse or vegetation types across the five DRIFT sites (refer to Section 4.2.1)

Landuse or vegetation type	Coverages											
	Northern		Western		Central		Eastern		Southern		Total	
	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
1	1.6	1.9	0.5	0.2	3.9	3.6	2.2	1.5	16.3	3.2	17.8	3.0
2	0.1	0.1	0.2	0.1	6.5	6.0	3.2	2.2	20.9	4.1	21.0	3.5
3	5.1	6.2	15.6	7.8	0.1	0.1	1.9	1.3	23.0	4.5	28.1	4.7
4	51.1	62.5	139.9	69.7	7.1	6.5	22.3	15.5	184.5	36.1	235.7	39.7
5	0.6	0.7	3.9	2.0	0.4	0.4	0.4	0.3	5.0	1.0	5.5	0.9
6	14.0	17.1	25.5	12.7	16.6	15.2	24.3	16.9	73.1	14.3	87.1	14.7
7	9.0	11.0	13.8	6.9	59.8	54.7	74.6	51.9	157.2	30.7	166.2	28.0
8	0.4	0.5	1.1	0.6	14.8	13.6	14.9	10.4	31.8	6.2	32.2	5.4
Total	81.8	100.0	200.6	100.0	109.2	100.0	143.6	100.0	58.4	100.0	593.6	100.0

For each of the DRIFT sites, daily time-series were computed for the following hydraulic[308] habitat variables:

- channels:
  - average depth,
  - maximum depth, and
  - average velocity;
- channel margins:[309]
  - average depth per (landuse/vegetation) type,[310]
  - maximum depth per type,
  - total wetted area per type, and;
- floodplain/marsh:
  - average depth per type,
  - maximum depth per type,
  - total wetted area per type,
  - wetted area per depth class for fish/birds.

Depth classes were defined by depth ranges identified as constituting critical (hydraulic) habitat for indicator vegetation communities, and fish and bird guilds.

In addition to the above, for the Marsh, the wetted area per depth class for vegetation was determined on a seasonal basis using 11-day average minima (dry season) and maxima (wet season). Broadly, this accounts for the fact that rooted vegetation, unlike fish and birds, takes time to alter its spatial distribution in response to changes in available hydraulic habitat.

[308] not all are 'hydraulic', as the depth classes have been determined for specific biota
[309] 20 m wide
[310] five (aggregated) types were used (refer to Section 5.3.2): landuse/vegetation types [1]+[2], [3]+[4]+[5], [6], [7], and [8]

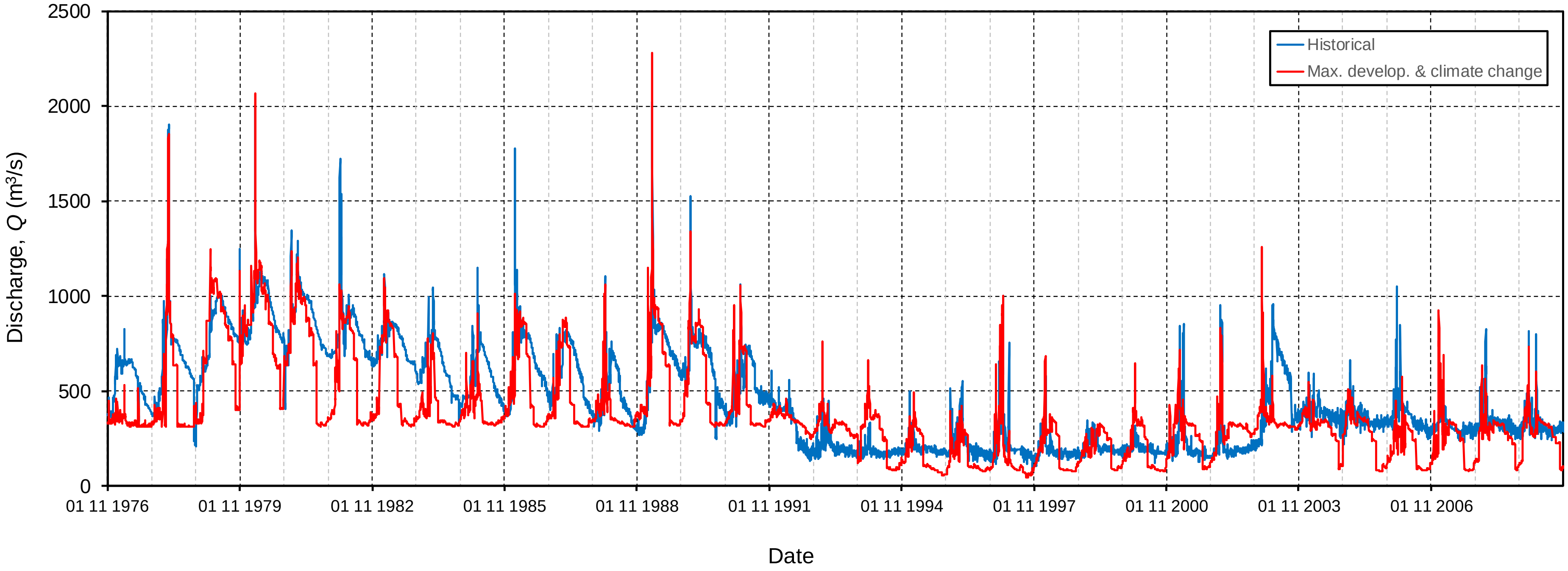

Figure 5.8 Daily discharge time-series at Chikwawa for the 33-year period 1976 to 2009: historical (measurement-based), and the 'maximum development and climate change' scenario

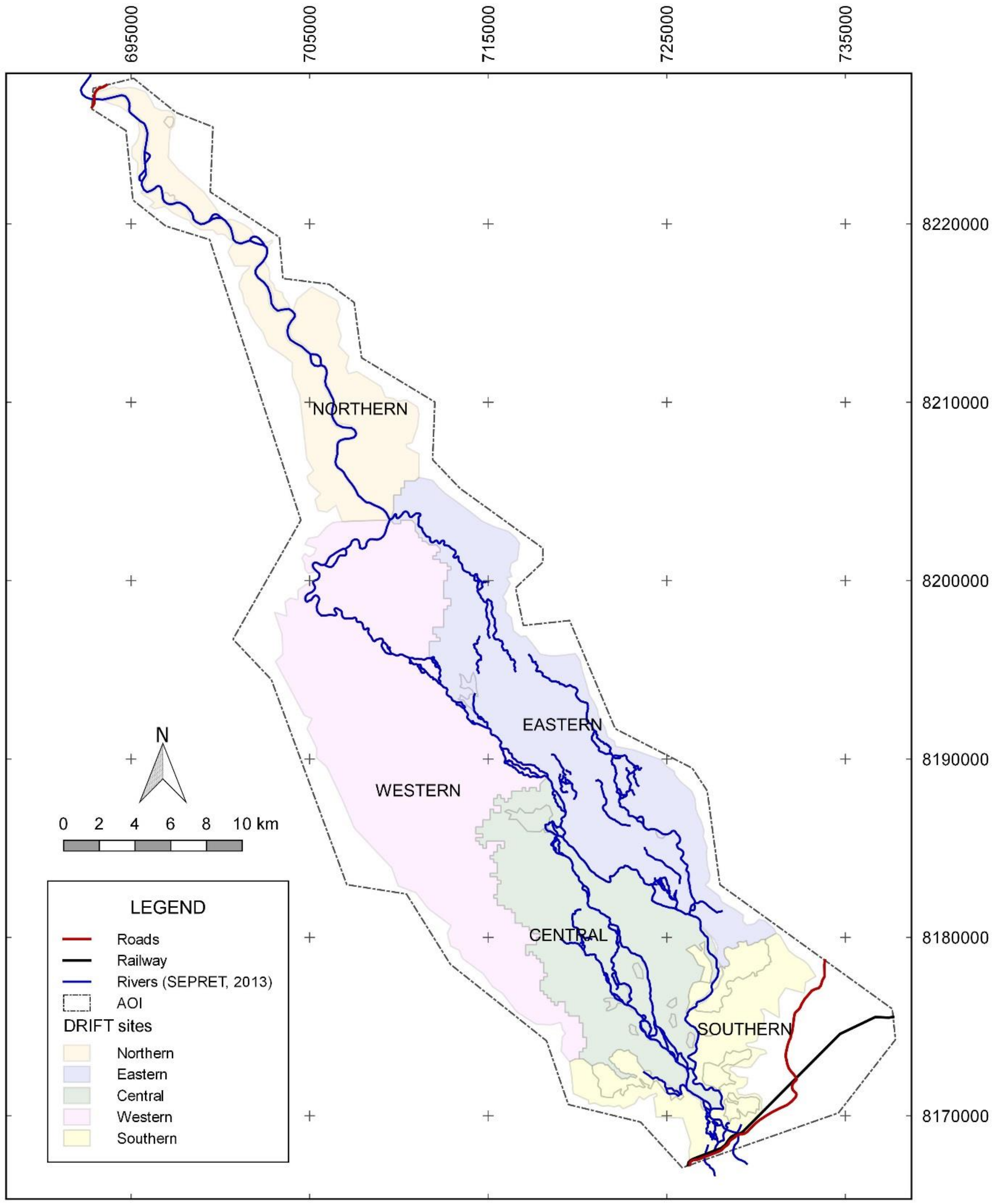

Figure 5.9 Delineation of the modelled area between Chikwawa and Chiromo into five DRIFT focus areas or sites, showing the location of lake areas (internal polygon shapes) within these; CRS is Arc 1950 (Malawi)

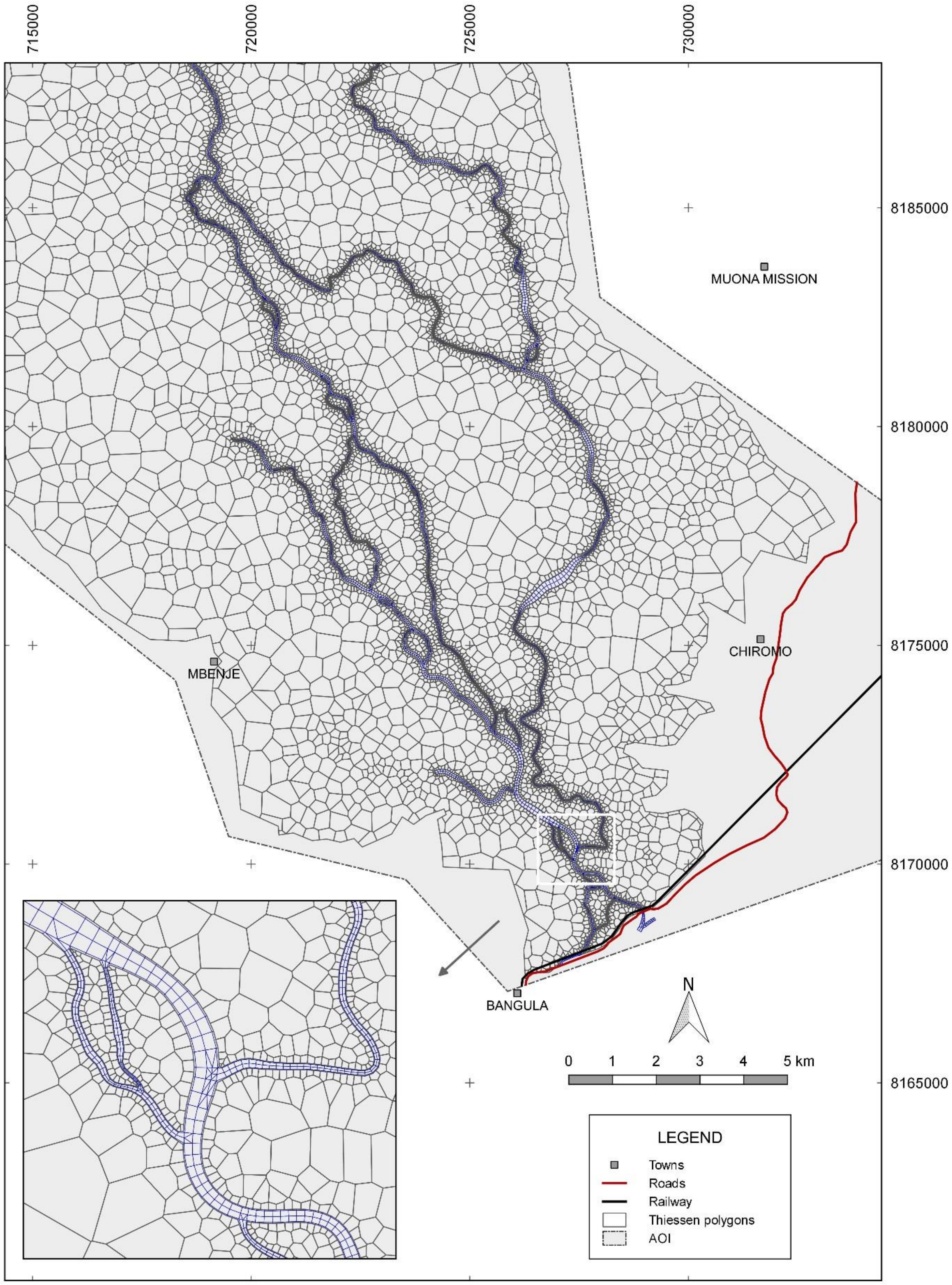

Figure 5.10 Thiessen polygons constructed over the floodplain/marsh regions of the modelled area; CRS is Arc 1950 (Malawi)

Post-processing was a challenge from a computer memory perspective, due to the large number of nodes processed (26 532) and time steps (12 045), combined with the seasonal basis used to characterise hydraulic habitat for vegetation. Computations were done on a nodal basis:

- for the floodplain/marsh areas, the 50-m grid (resampled from the 2-m DEM - refer to Section 5.3.2) was used with each grid (or cell) defined by its position in the marsh, ground elevation, type (i.e., landuse/vegetation), node and DRIFT site;
- for the channel margins, a 5-m grid was used within a 30-m buffer of the channel banks (defined by the same parameters as above), and;
- for the channels, nodes along the centre-line were used.

Depths per node were calculated from the differences between water surface (results of the hydrodynamic modelling) and ground elevations, and these were used to compute, *inter alia*, time-series of averages, maxima, and wetted area falling within specified depth classes (or ranges) for each of the landuse/vegetation types, per site. These are the ecologically-relevant hydraulic habitat variables (or indicators) used in the DRIFT DSS.

5.5.3 Attenuation capacity of the Marsh

The hydrodynamic model is also needed for a flow-related aspect of the Environmental Services sub-study, *viz*., the effect of the Marsh on the Shire River downstream, specifically, flood control. This was done in the model by 'removing' the Marsh, and assessing changes to the flow behaviour at its downstream end, i.e., at Chiromo.

This is not completely straightforward, as what defines 'removal' of the Marsh needs to be considered. For this assessment, 'removal' denotes the indigenous marsh vegetation (i.e., papyrus, reeds and grasses). It is inevitable, however, that changes in the composition and distribution of the Marsh's vegetation will be accompanied by changes in the morphology. Arguably, the process of channelisation is the largest risk to loss of marsh habitat. Findings presented in the next chapter indicate that both the channels and adjacent floodplain/marsh areas are experiencing sedimentation. This, combined with the view that sediment delivery to the Marsh is unlikely to be substantially reduced in the (near) future, leads to an assessment of a low risk of future channelisation (refer to Section 7.3). Therefore, for this assessment of the Marsh's attenuation capacity, the existing topographical template has been left unaltered (i.e., the same morphology but without marsh vegetation). In the modelling, a set of uniform hydraulic characteristics, representing low resistance to flows, were specified throughout. Although this is a somewhat drastic change from the existing condition, it is indicative of a worst-case 'no Marsh' scenario, but with the present topography. Simulation was run for the 13-year period, 1996 to 2009, using the historical flow regime.

The modelling indicates a moderate change in the attenuation capacity: Shire River peak outflows (average daily) from the Marsh increase by up to ~20%. The upper range is associated with shorter duration events of higher magnitude. Within the context of climate change: anthropogenically-induced climate change projections (refer to Section 3.5.1 in the hydrology chapter) consistently predict increases in the proportion of rainfall falling in heavy events during the wet seasons. Flood inundation is related to water level and topography, and not discharge, *per se*. It is therefore informative to estimate approximate increases in water level: applying the rating relationship developed for the Shire-Ruo confluence (i.e., as plotted in Figure 5.5), for Shire River flood peaks of ~1 000 and 2 000 m^3/s (i.e., neglecting the influence of the Ruo), water levels can be expected to rise by about 0.5 and 0.75 m, respectively.[311] Further downstream along the lower Shire River these values

[311] near the pre-2015 Shire-Ruo confluence

could be less as flows inundate over a wider floodplain. Considering simultaneous flooding of the Ruo (of equivalent peaks to the Shire), a 'marsh' with degraded vegetation, the above values can be expected to reduce by about three-quarters, i.e., ~0.5 m for a combined Shire/Ruo peak discharge of ~4000 m^3/s. Although these are not inconsequential increases in water level for floodplains of low relief, they are much less than those indicated in the next chapter (dealing with sedimentation of the Marsh), which shows that siltation has increased water levels by up to ~4m near the Shire-Ruo confluence, over the last 30 years or so.

The above assessment is for the pre-2015 routing of the Ruo's course into the Marsh through Lake Tomaninjobi. In the short-term, this may attenuate the Ruo's flood flows, but it is likely to be short-lived. This is because of siltation (and thus reduced flow storage and thus attenuation capacity) of the lakes and downstream channels in the southern region of the Marsh, which has already begun in Lake Tomaninjobi. This is discussed further in the next chapter on Marsh sedimentation.

6 Upstream catchment landuse and Marsh sedimentation

6.1 The upstream Shire River Basin

The except below from the World Bank 2012 project appraisal report, in support of the first phase of the SRBMP, provides an overview of the situation in the Shire River Basin:
"*High population density and poverty have led to substantial human pressure on the environment and degradation of the Shire Basin's natural resource base, notably land and forests. The growing population expands land area under cultivation and exploits forests and woodlands for firewood and charcoal production. Deforestation, soil erosion and sedimentation form the most serious threats to the environment and natural resource base in the Shire River Basin, resulting in the increased incidence of erosion, run-off and flash floods. High loads of sediment are deposited in river beds, reservoirs and floodplain wetlands, affecting irrigation canals, fisheries and hydropower generation. Water resources are increasingly degraded through silt loads, sedimentation, etc. These problems are a direct result of catchment degradation, unsustainable land use and management practices, and increased use of chemical fertilizers without complementary soil and water conservation measures*."

The following more detailed history of human pressures and catchment responses have been compiled from Pike (1968a) and Kaunda and Mtalo (2013), and suggests that catchment degradation dates back some time. Tophan (1939)[312] noted that very little of the vegetation was in its natural state at that time.

Since 1920, the population within the Shire Basin increased rapidly, not only due to a high rate at that time of about 2.5% pa, but also from substantial immigration from neighbouring Mozambique. During the mid-1920s to 1930s, a succession of droughts and famines in the region caused large-scale population movements from drier areas into the relatively better-watered and more fertile areas of Malawi. From 1948, agriculture transitioned from purely subsistence toward a subsistence/cash-crop economy. This necessitated the clearing of larger areas of woodland for cultivation, coupled with land requirements for the increasing populace. These increases in population and agricultural tempo affected the natural rates of run-off, but the extent of this was difficult to ascertain. Pike (1968a) remarks that experience[313] elsewhere in central Africa had shown that runoff had increased, particularly in the Zambezi and Kafue River catchments, where there had not been large population influxes, thus inferring increased rainfall.

Malawi (formerly known as Nyasaland) attained independence in 1964. It was a one party and authoritarian state between 1964 and 1994, and governed as a multiparty democratic country after 1994. Laws and regulations were easier to enforce pre-1994 than the recent democratic era, and there has been the suggestion that this has led to accelerated environmental degradation over the past two decades. Deforestation (Figure 6.1) and environmental degradation in general are two of the major challenges facing the country. For instance, nationally, forest cover is reported to have declined by 7% between 1990 and 2010 (Kaunda and Mtalo, 2013), but values from this study for the upper and middle Shire Basin are ~four times this (refer to Table 6.3).

[312] as cited by Pike, 1968a
[313] at that time

Figure 6.1 Top: Deforestation, Mount Mulanje[314] (photograph credit Marie-Marthe Gagnon, 2009); bottom: Malawi charcoal sellers (Nyasa Times, 2015)

The CIA World Fact Book gives a 2015 population growth rate of 3.3%, with Malawi ranked sixth world-wide[315] for 225 countries listed (i.e., in the highest 3%). Its present population is ~18 million.[316] The population growth, especially in the southern region where the Elephant Marsh is situated, is partly due to the influx of refugees from Mozambique who fled the 1977 to 1992[317] civil war, and did not return. Roughly 85% of the populace live in a rural setting, with most engaged in subsistence agriculture relying on rainfall, and recession agriculture as practised along the floodplains of the lower Shire River and in the Marsh. In rural Malawi, where most people reside, firewood is simply the only type of fuel, whereas charcoal is more commonly used in urban areas. Of the charcoal produced, almost 60% comes from protected trees in forest reserves and national parks (AG, 2015). National

[314] The Ruo River rises on the slopes of Mount Mulanje
[315] The world average varies between ~1.18 and 1.22, depending on the data source.
[316] http://countrymeters.info/en/Malawi
[317] hostilities and tensions resurfaced in 2013

access to electricity is low at 7 to 8% and, in rural areas, is even less at ~1% (Kaunda and Mtalo, 2013). Many households in urban areas that have access to electricity use charcoal[318] either during load shedding and because electricity is so expensive. The tobacco industry is also a major consumer of this resource, which it uses in fire-cured drying processes. Consequently, unsustainable tree harvesting has led to uncontrollable loss of forest cover: Malawi has the fifth-highest rate of deforestation, worldwide (AG, 2015).

There a few recent studies that quantify these changes in landcover, including Palamuleni (2009; 2011) and Mott Macdonald (2015). The high resolution (30 m) landcovers[319] for Malawi produced by Kabatha (2014) also provide evidence of the changes between 1990 and 2010.

Palamuleni (2009; 2011) investigated the hydrological impacts of landcover changes in the upper Shire Basin. The focus area extended from Lake Malawi to ~50 km downstream of Liwonde, an area of ~4 500 km^2. An examination of potential landcover information for use in the study revealed a lack of systematic and reliable national coverage, with existing data being fragmented: temporally, spatially, and concerning thematic detail and methodology. Typically, landcover classes had previously been evaluated using visual interpretation of printed images. This prevented the use in that study of existing information on historic catchment condition, and hence in this study.

Palamuleni (2011) used remote sensing techniques (Landsat imagery) to inventory temporal changes in landcover between 1989 and 2002. The results indicated substantial changes in the magnitude and direction of change over the 13 years, particularly concerning human habitation and related activities: transitions were from woodlands/shrubs to mostly cultivated/grazing and built-up areas (Table 6.1). The effect of these changes on the hydrology of the upper Shire River was investigated using the Soil and Water Assessment Tool (SWAT). Results showed that surface runoff patterns in this catchment were strongly influenced by the landcover changes. Deforestation, land fragmentation, cultivation of wetlands and a rapid increase in human settlements have substantially increased runoff elevated flood peaks with more-rapid catchment response; and reduced groundwater recharge thereby reducing dry season flows.

Table 6.1 Landcover changes for a 4 500 km^2 catchment area in the upper Shire Basin (Palamuleni, 2011)

Class	Area (1 000 ha)		Change in area (1 000 ha)
	1989	2002	
Fresh water	38.4	37.2	-1.2
Built-up areas	14.3	39.8	25.5
Cultivated/grazing	95.4	117.0	21.6
Marsh	6.4	29.5	23.1
Grasslands	15.1	63.7	48.5
Savanna shrubs	178.0	112.4	-65.7
Woody open	70.6	38.5	-32.2
Woody closed	37.9	18.5	-19.5

Mott Macdonald (2015) provided a series of landcovers for 4 years: 1972, 1992, 2000 and 2010 for four sub-catchments in the upper Shire Basin (the Chingale, Kapachira, upper Lisungwi and

[318] It can be packaged and has a higher energy efficiency.
[319] available from MASDAP at http://www.masdap.mw

Wamkulumadzi). The sub-catchments are substantially smaller (~one-tenth) of the upper Shire Catchment considered by Palamuleni, but reveal the same picture, *viz.*: losses in forest cover and increases in crop cover. For these four sub-catchments over this 38-year period, the changes in forest and cropland were in the ranges -6 200 to -9 280 ha, and 6 000 to 9 800 ha, respectively. Combining all sub-catchments (total area of 129 000 ha), forest had reduced from 72.2 to 39.6 (i.e., decline of 45.2%), and cropland had increased from 57 400 to 88 700 ha (i.e., increase of 54.6%). Noticeable is that nearly three-quarters of the 38-year losses of forest cover, and gains in croplands, occurred in the earlier period (1972 to 1992), i.e., under the more 'authoritarian' government. Although the values in Table 6.2 infer a reduced rate of decline in forest cover after 1992, in the Kapachira status quo report, Mott Macdonald (2015)[320] describe a study in the Kunthembwe Traditional Authority that showed that forest cover declined from 15 600 to 1 500 ha between 1994 and 2005 (i.e., a 90% loss in 11 years).

Table 6.2 Landcover changes for four sub-catchments (totalling 1 290 km^2) in the upper Shire Basin (Mott Macdonald, 2015)

Sub-catchment (area, 1 000 ha)	Landcover	Area (1 000 ha)				Overall change in area (1 000 ha)
		1972	1992	2000	2010	
Chingal (41.26)	Cropland	23.89	29.68	29.68	30.41	6.52
	Forest	17.37	9.94	10.77	10.00	-7.37
	Grassland	0.00	1.03	0.15	0.16	0.16
	Wetland	0.00	0.61	0.65	0.66	0.66
Kapachira (33.16)	Cropland	0.22	2.36	2.32	10.04	9.82
	Forest	32.94	30.80	30.84	23.01	-9.93
	Wetland	0.00	0.00	0.00	0.11	0.11
upper Lisungwi (25.96)	Cropland	17.27	22.42	22.51	23.31	6.04
	Forest	8.49	3.34	3.28	2.31	-6.18
	Grassland	0.00	0.00	0.00	0.12	0.12
	Wetland	0.00	0.00	0.00	0.031	0.031
	Built-up	0.00	0.00	0.00	0.0067	0.0067
Wamkulumadzi (29.56)	Cropland	16.02	25.72	25.64	25.00	8.98
	Forest	13.44	3.74	3.77	4.27	-9.17
	Wetland	0.00	0.0	0.0	0.014	0.014
All (129.94)	Cropland	57.40	80.18	80.15	88.76	-31.36
	Forestland	72.24	47.82	48.66	39.59	32.65

Kabatha (2014) produced a series of landcover maps for Malawi that are available from the Malawi Spatial Data Portal[321] (MASDAP). The maps were developed from Landsat imagery[322] using supervised classification, with image interpretation carried out per scene. Images used for classification were selected based on seasonality, with preference for the dry season. Maps were developed for three epochs: 1990, 2000[323] and 2010. The classification scheme (Type II) was informed by country specific interest, definitions, descriptions, mapping goals and policy statements and documents with guidance from IPCC guidelines.

[320] data source: Blantyre District Socio-Economic Profile (DSEP) 2007-2010
[321] http://www.masdap.mw/
[322] 30-m resolution
[323] The 2000 cover has a different number of classes, and could not be reconciled with those from 1990 and 2010.

The Kabatha (2014) national landcovers were clipped to an area of the Shire Basin between Liwonde and Chikwawa (10 150 km^2), using the relevant WRUs from Atkins, 2012 (refer to Figure 3.1), and are plotted in Figure 6.2. This sub-catchment represents the source area for sediment loads in the Shire River at Chikwawa (i.e., the upstream boundary of this study's AOI). The results are presented in Table 3.1 and plotted in Figure 6.3 for twelve of the landcover classes,[324] expressed as areas, and as the percentage change in area over the two decades as a proportion of total catchment area. For this upstream catchment (even given a different time period[325]), the results are consistent with those from other studies that considered smaller sub-catchments: increases in cropland at the expense of forestry, to the order one-third of the catchment area.

Table 6.3 Landcover areas and change (1990 to 2010) for the 10 150 km^2 sub-catchment area between Liwonde and Chikwawa, calculated from the classification of Kabatha (2014)

Landcover class		Area (km^2)		Change relative to catchment area (%)
ID	Description	1990	2010	
1	Dense forest	190.3	30.1	-1.6
2	Moderate forest	326.6	467.1	1.4
3	Sparse forest	5307.4	2099.9	-31.7
4	Closed grassland	3.6	9.4	0.1
5	Open grassland	9.3	57.3	0.5
6	Closed shrubland	317.7	139.8	-1.8
7	Open shrubland	707.8	1087.3	3.7
8	Perennial cropland	15.3	18.8	0.0
9	Annual cropland	2911.4	5965.8	30.2
10	Wetland	210.1	24.0	-1.8
11	Waterbody	33.2	37.1	0.0
12	Settlement	8.5	138.8	1.3

There is a dearth of direct measures for soil loss or increased sediment loads in rivers because of deforestation and land degradation. Tamene (2011) applied geospatial techniques to model soil erosion, which was used to identify priority sub-catchments in the upper Shire Basin where conservation measures could reduce sedimentation in downstream reservoirs and improve the sub-catchment's ecosystem services. The identified priority areas also informed the selection of sub-catchments used in the Mott Macdonald (2015) project, listed in Table 6.2.

[324] 'otherland', 'clouds' and 'cloud cover' are not listed
[325] *viz*. 1990 to 2010, cf. 1989 to 2002 (Palamuleni, 2009) and 1972 to 2010 (Mott Macdonald, 2015)

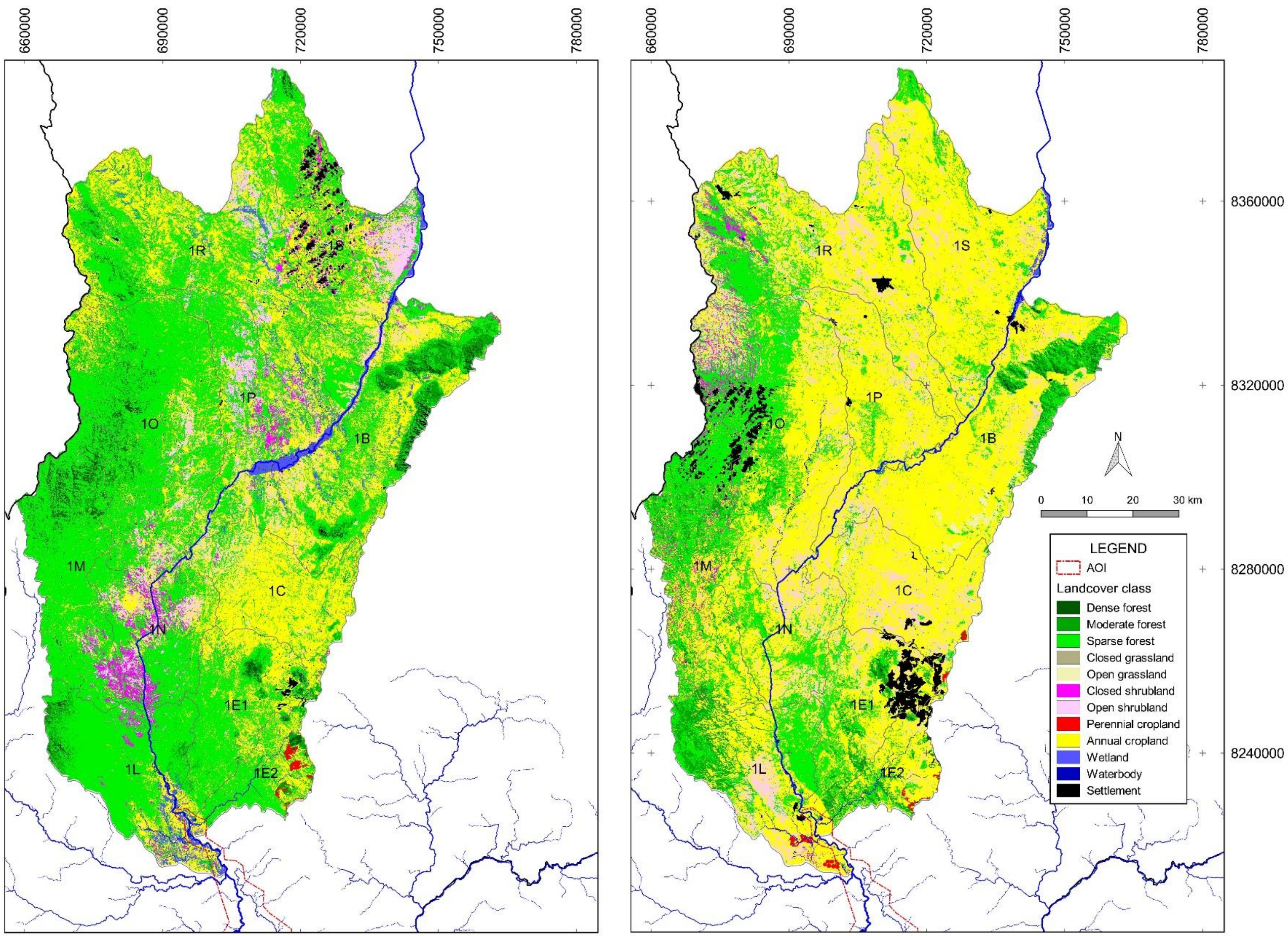

Figure 6.2 The Kabatha (2014) national landcovers for 1990 (left) and 2010 (right) clipped to the Shire Basin between Liwonde and Chikwawa

Tamene (2011) cautions against the use of his soil loss estimates as precise values but, given the lack of *any* quantitative information on sedimentation, it is informative to note these and other values. Tamene's (2011) average annual soil loss estimate for the Shire Basin is 34 t/ha/an[326] - well within the high loss range for Malawi of 10 to 43 t/ha/an (EAD, 2002). It is considerably higher than the tolerable range of 10 to 12.5 t/ha/an given by Amplett (1986) and the rate of soil formation of 12 t/ha/an (EAD (2002). Comparative values cited include: an average rate for Malawi of 20 t/ha/an (Bishop, 1995; Nakthumwa, 2004); upper range of 50 t/ha/an from spot trials for various cover and farming activities and erosion hazard mapping (Kasambara, 1984; Machira, 1984; Amplett, 1986; Khonje and Machira, 1987); regional values of 13 to 29 t/h/an and average of 20 t/ha/an (Wold Bank, 1992). Although Tamene notes that the results of the study are in general agreement with those of others cited, the average (*viz*. 34 t/ha/an) is in the upper range. This is not unexpected, however, given that landcover was derived from 2005 Landsat imagery, which post-dates most of the studies by a decade or more.

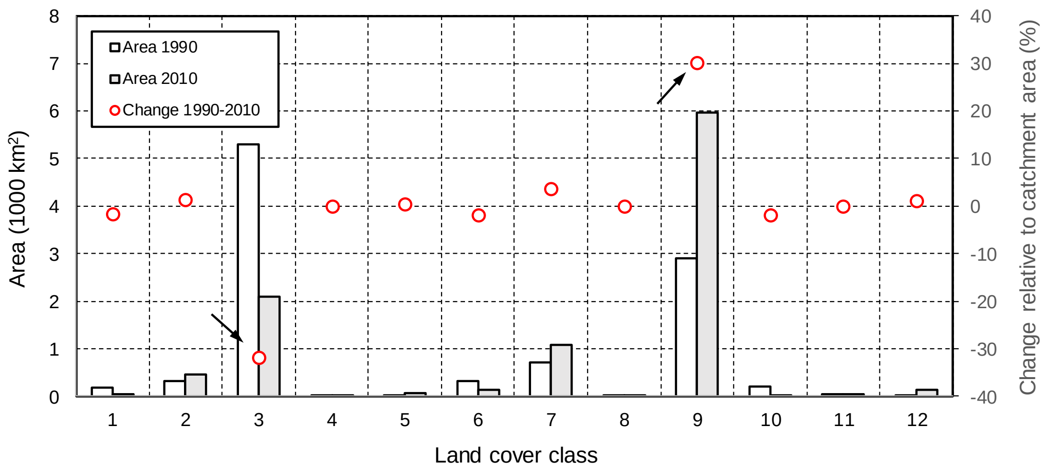

Figure 6.3 **Landcover areas and changes between 1990 and 2010 for the 10 150 km^2 sub-catchment area between Liwonde and Chikwawa, calculated from the classification of Kabatha (2014); class descriptions are given in Table 6.3; the classes with substantial changes are indicated with arrows**

The most apparent and alarming direct evidence of high sediment loads in (or delivery to) the Shire River, is probably the siltation of the reservoirs upstream of the HPPs. These are filled with sediment, which hampers daily operation and the generation of electricity.[327] This is patently apparent in Figure 6.4, which shows Kapachira Reservoir during 'desilting' in March 2016. Figure 6.5 shows the operational costs of and power lost through desilting activities from 1999 to 2010 (data obtained from ESCOM),[328] but not the quantities of sediment removed. Over this 12-year period, the capital expenditure on desilting was US$ 355 000[329] with incurred operational costs of US$ 96 000.

A reasonable correspondence between the extent of siltation and the associated distribution of operational costs would be expected, although the dates of equipment acquisition are also relevant. Nevertheless, the increase in costs during the early 2000s corresponds closely with a change in the (regulated) base flow regime, as well as high wet-season flows during 2001 (refer to Figure 4.26) and 2002, after a few years of low wet-season flows (Figure 3.8).

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[326] tons per hectare per annum
[327] Aquatic plants have also, but are not of direct relevance to the hydromorphology sub-study.
[328] Eliot Taylor (Mott Macdonald), pers. com.
[329] At the November 2016 rate of exchange

Figure 6.4 Siltation of the Kapachira Reservoir, exposed during 'desilting' in March 2016; photograph taken looking downstream towards the dam wall on the far-right

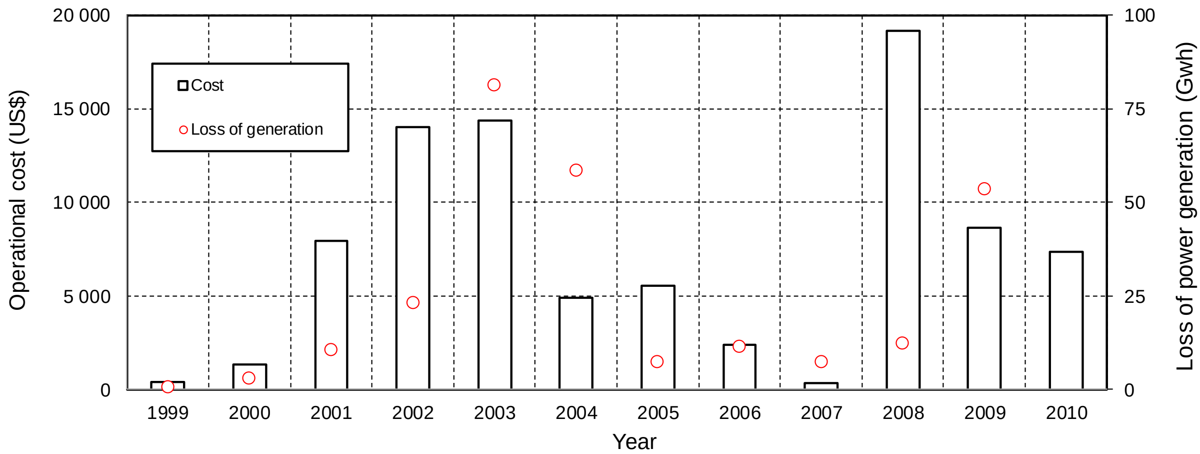

Figure 6.5 Total operational costs of desilting activities at the Nkula, Tedzani and Kapichira hydropower stations, and loss of power generation due to siltation, for the period 1999 to 2010 (data sources: ESCOM and Mott Macdonald[330])

Future projections are that climate change (Chapter 3) will exacerbate an already dire situation. The GCMs applied by Van der Weerts and Wright (2015) indicate that erosivity[331] will increase by 14 to 17% around the mid-21st century, and by 19 to 39% towards the end of the century. The authors express the situation as follows: "*Unless land management practices in the future are substantially improved, soil erosion will increase drastically. Considering that some 80% of the flow in the Shire River consists of sediment free outflow from Lake Malawi, the sediment inflow from the tributaries in the*

[330] Eliot Taylor, pers. com.

[331] 'erosivity' is a measure of the potential ability of soil, regolith, or other weathered material to be eroded by rain, wind, or surface runoff (Encyclopaedia of Natural Hazards; part of the series Encyclopaedia of Earth Sciences Series pp 289-290)

Shire Basin is huge. Increased erosion losses in the catchments of these tributaries will bring sediment transport and deposition to an even higher level."

Although there are no data on sediment loads or their trends over time, other evidence points to excessively high sediment loads in the Shire River (Figure 6.4). Furthermore, it appears that this has been the case for some time (Table 6.2 and Figure 6.6; Tophan, 1936 and Pike, 1986a). Predictions are that (anthropogenic) climate change will worsen the situation, and the need for drastic conservation measures cannot, therefore, be overemphasized.

Figure 6.6 Gulley erosion in upper Wamkulumadzi where rehabilitation effort has met with little success (Mott Macdonald, 2015)

6.2 The Marsh

6.2.1 Description and conceptualisation

As was the case for the upper Shire River, there are no quantitative data on sedimentation in the Marsh, so any assessment of Marsh sedimentation must rely on secondary data such as aerial photography and remote sensing, augmented by field observations.

Figure 6.7 is plot of the lower Shire River's longitudinal profile using SRTM (30 m resolution) remote sensing data, and for an intermediate stretch between Chikwawa and Chiromo (AOI) from DGPS/sonar surveys carried out during this study (refer to Section 5.2.2.2). Within the AOI, the profiles compare remarkably well.[332] The abrupt reduction in gradient below Kapichira Falls (16 km upstream of Chikwawa) marks the change to a downstream river that is less laterally-confined and with lower transport capacity (reduced slope); a consequence of which is the lower-energy floodplain system which extends to the Zambezi River confluence some 110 km downstream of Nsanje. It is thus important to recognise that the lower Shire River system is characterised by natural sedimentation,[333]

[332] reassuring, given that SRTM data has been found to have an absolute error of around 5 m on the African continent (Rodriguez *et al.,* 2005 and Farr *et al.,* 2007, as cited by Meier, 2012)
[333] refer to the dating of sediment cores in Section 6.2.1

but the recent upstream changes in landcover intimate escalation in the rate of soil loss and associated sedimentation.

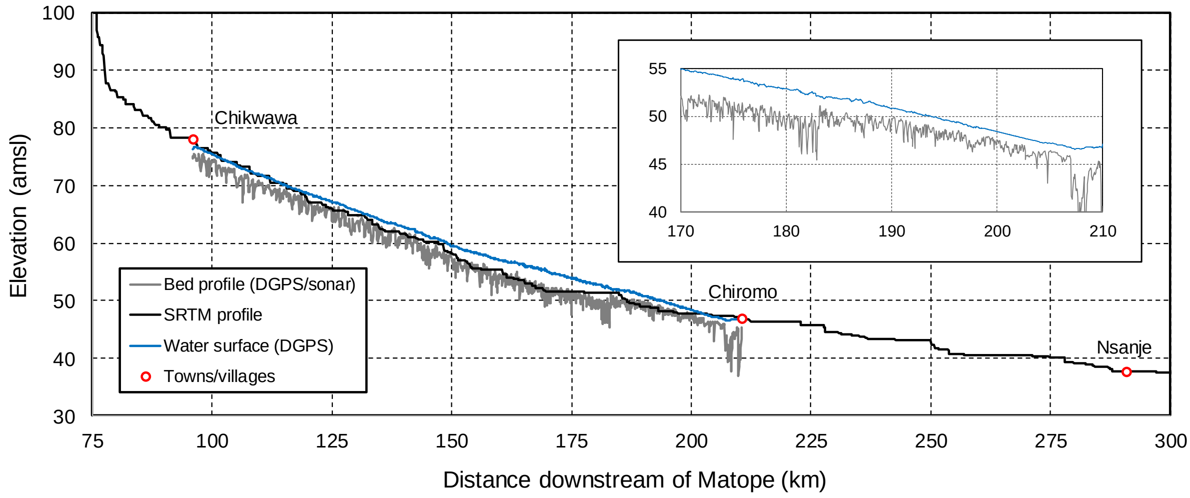

Figure 6.7 **Longitudinal profile of the lower Shire River (DGPS survey and SRTM); inset is a magnification of the 40 km stretch upstream of Chiromo**

The high sediment concentrations carried by the Shire River and tributaries flowing into the Marsh are indicated by, or may be inferred from the fine alluvial bed material in, the photographs of Figure 6.8. In recent times, flooding along the lower Shire River Valley has been synonymous with widespread sedimentation, as illustrated in Figure 6.9 from photographs taken near Chikwawa, Bangula and further downstream. Other signs of high sediment loads and the propensity for sediment accumulation are from the images in Figure 6.10 (top), which show alluvial fans developed on the Marsh's margins by the Chidzimbi River (refer to Figure 4.6) and the Ruo River during the floods of 2015. Alluvial fans are associated with many of the tributaries (e.g., Mwamphanze River) that flow into the Marsh from the Thyolo Mountains, and form where they encounter the flatter marsh topography.

The high resolution aerial photographs in Figure 6.10 (middle and bottom) provide visual evidence of sediment-filtering in the Marsh. The difference in colour of flow that has filtered through vegetation (dark green) and turbid water (light brown) that has largely remained in the main-stem channel, is most apparent at the indicated distributary junctions. The (streamline) separations between the clearer and more turbid water, over some distances downstream of the junctions, attest to flowing (i.e., not pools) of clearer water.

The remote sensing image (March 2015 Landsat) in Figure 6.10 (top-right), also reveals the difference between sediment-laden (light blue) and relatively less turbid (dark blue) flows associated with the Ruo and Namichimba/Shire, respectively. Given the present realignment of the Ruo River's course into Lake Tomaninjobi, the future loss by infilling of this and other southern lakes is deemed inevitable.

Figure 6.8 **Top (28 February 2015): the turbid waters of Shire River at Chikwawa one-and-a-half months after the flood peak (left), and (right) the dark brown sediment-laden waters of the Ruo River flowing into the south-eastern marsh; middle: the ephemeral Mwanza River on 28 February 2015 (left) and September 2016 (right) - note the removal of a few large trees in the interim; bottom: the fine alluvial bed of the Thangadzi West which flows into the southern marsh near the town of Bangula (refer to Figure 4.6)**

Figure 6.9 Sediment deposits associated with the 2015 flood, top: the floodplain at Chikwawa; middle: looking downstream towards the breached railway embankment near Bangula; bottom: floodplain downstream of Chiromo[334]

[334]photograph credits: top: http://www.aljazeera.com/news/africa/2015/01/malawi-faces-unprecedented-flood-disaster-201511774238313771.html; middle: Ashley Cooper (globalwarmingimages.net) https://www.theguardian.com/global-development/gallery/2015/apr/29/malawi-scale-devastation-january-floods-unfolding-in-pictures ; bottom: https://www.irisglobal.org/relief/malawi-mozambique-flooding-2015/news/pictures-of-the-flood-in-malawi-feb-27-2015

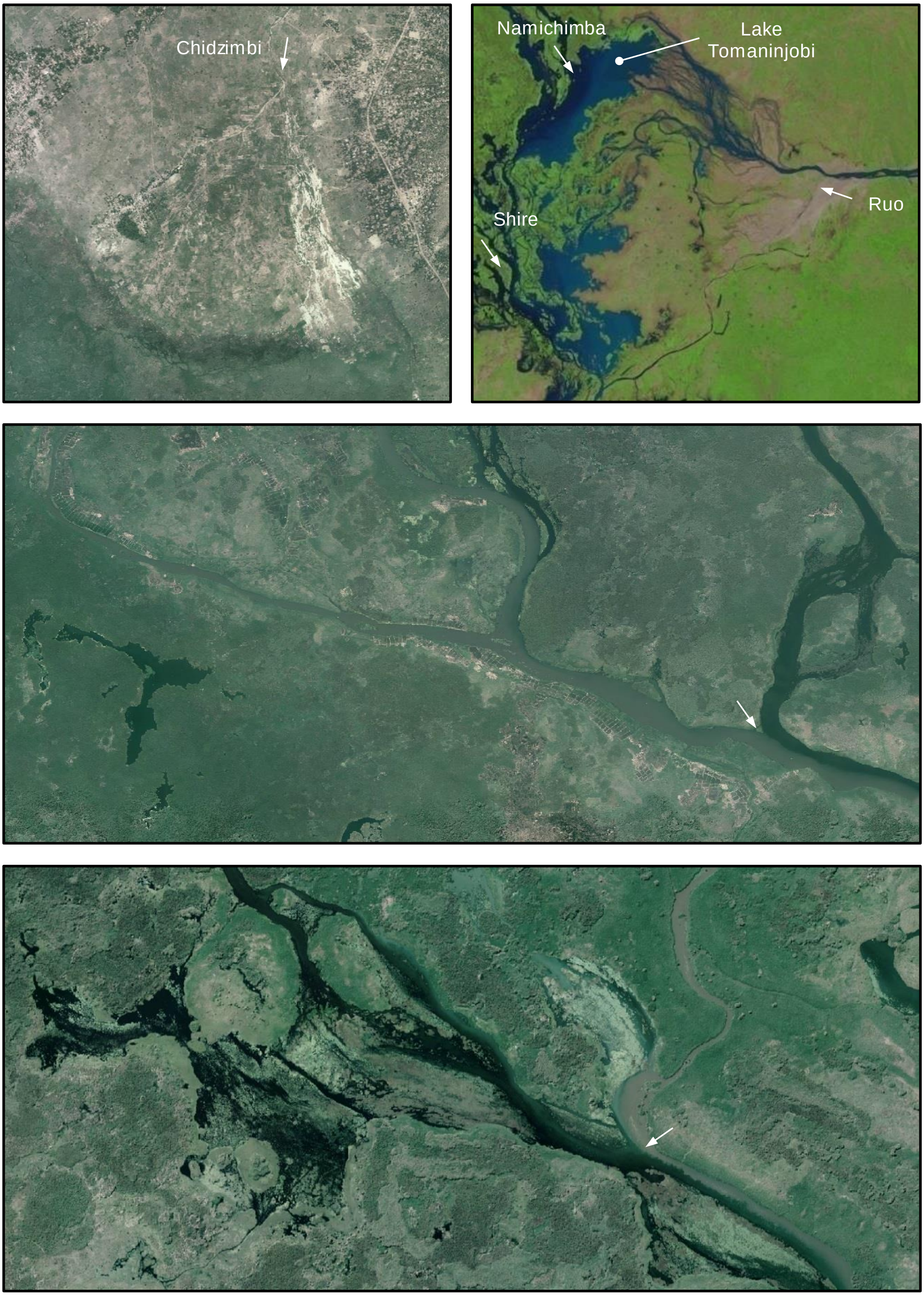

Figure 6.10 Top: Alluvial fans on the edge of the Marsh formed by the Chidzimbi Tributary (left) and Ruo River (right) (refer to Figure 4.6); middle and bottom: dark green (low turbidity) and light brown (turbid) flows at distributary confluences (see arrows) in the Marsh, indicating effective sediment-filtering by marsh vegetation

A conceptual understanding of the historical formation of the generally shallow lakes in the Marsh is valuable, since it provides a better basis for assessing resilience to change and potential future loss of these important morphological features and marsh habitats. Their locations provide the necessary insight, since the larger water bodies all occur along historic and/or existing channel courses through the Marsh: the two arms of Lake Bangula are associated with the south-western paleo course of the Shire. Abandonment of this course, discussed previously, appears to have left topographical depressions in the marsh landscape. These lakes are now essentially backwater features, with levels controlled at their downstream junction with the Shire River (Figure 4.24), except during high flows when water enters from upstream. Recently, low levels have been experienced in these lakes, which have presented water quality problems[335] for the adjacent Kaombe Sugar Estate that abstracts irrigation water from the lake through a connecting canal.[336] The low levels and recent desiccation (Figure 6.11) are attributed to a combination of: decreasing discharges in the Shire River, and progressive lowering of the Shire's channel bed (and controlling water level) along the alternate right-bank distributary (refer to Figure 2.12 and Figure 4.23u).

Figure 6.11 Photographs of Lake Bangula, November 2016, showing recent desiccation of lake habitat (photograph credit: Bruce Carruthers)

[335] The extent of which is jeopardising the future viability of the estate.
[336] Bruce Carruthers, pers. com.

There are two lakes in the central and northern region of the Marsh (illustrated in the landcover mapping of Figure 4.28; labelled 'f' and 'd', respectively) that are located in areas immediately upstream of the channel confluences a/b and b/c, in Figure 4.15. Two of these channels (c, and the downstream stretch of a) were progressively abandoned in the 2000s. A photograph of lake 'd' (Figure 4.28) is illustrated in Figure 6.12d, and was found to be very shallow (generally less than half a metre) in October 2015.

Tomaninjobi, the largest of the lakes, is also the only lake in the Marsh through which a channel flows: the sediment-filtered waters of the lower Namichimba (Figure 6.10 top-right). The historic courses of tributaries flowing from the Thyolo Escarpment (as mapped by Sclater and Beringer in the 1890s: Figure 4.3 and Figure 4.4, respectively) are likely to have contributed to its existence, through the formation of local depressions in the marsh landscape. The formation of the other generally shallow lakes between Tomaninjobi and Chiromo Bridge (Figure 4.7c and Figure 6.12e) can only be surmised, but it is reasonable to expect that their locations are also associated with paleo channel activity.

Figure 6.12 Photographs taken across some smaller and shallower lakes in the Marsh (September 2015) d: fishing from a dugout boat (or mokoro); e: the series of lakes north of Chiromo Bridge (refer to Figure 4.11)

6.2.2 Data collection

Data collection involved:

- the extraction of sediment cores, for purposes of dating and pollen analyses, and;
- the sampling of water columns in the rivers and distributary channels to determine sediment concentrations and other water chemistry variables.

6.2.2.1 Radiocarbon dating, pollen and diatom analyses of sediment cores

The first of four sediment cores was extracted during the scoping investigation in February 2015, at the margin of the floodplain near Bangula. Marsh inundation levels were still high after the flood of the previous month, providing limited access to exposed sites further into the Marsh. The purpose of the exercise was to test the viability of the equipment (a Johnson bucket auger)[337] and technique, and to provide a test sample whose dating would inform future planning and activities. As is the case with many field-based studies, the initial plan required adaptation, particularly given effects of the recent and extreme flood.

A test sample from the bottom[338] of the auger hole at 4.5 m was selected, and radiocarbon dated[339] at 6350 Before Present (BP).[340]

Subsequently, three sediment cores were collected from three different locations (Figure 4.19; Figure 6.13 bottom) distributed along the length of the Marsh from the Shire/Namichimba split to Chiromo Bridge.

Identification of sites considered the following:

- The ages of deposits (extracted from different depths) are used to infer rates of sedimentation due to an (assumed) vertical process of aggradation. The morphology associated with floodplain and marsh environments is characterised by considerable lateral channel movement, and a site located in a paleo-channel is unlikely to provide meaningful data. The mapping of channel change (Chapter 4) was valuable for informing the location of more-permanent sites not affected by channel migration.
- Aerial photography and the channel-change mapping indicated that, in many areas of the Marsh, habitation (and associated cultivation) occurs along the margins of active and historic channel courses (e.g., Figure 6.13). Such sites, while accessible, are unfavourable, since levee formation and may not reflect long-term and more recent trends in sedimentation of the mashes.
- It is not practical to extract cores (by augering) in inundated marsh vegetation.
- Accessibility of the sites using GPS.[341]

[337] Thompson type
[338] to provide an upper limit for age
[339] dating was done by Beta Analytic Inc., US
[340] Before Present is a time scale in years used to specify when past events occurred. Since the ‘present’ time changes, standard practice is to use 1 January 1950 as commencement date of the age scale, reflecting the fact that radiocarbon dating became practical in the 1950s.
[341] Any other (e.g., visual) means of navigating around the marsh is unwise, and generally impractical.

Figure 6.13 **Top (v): dwellings and fields on the marginally-elevated levee adjacent to the historic south-western course of the Shire River; bottom: sediment coring at site C3 in the Marsh using a bucket auger, with the Shire River in the distance; refer to Figure 4.19**

The original target was ten samples (including the test one) from five cores, i.e., nine plus one. It was decided that three samples from three cores would better inform sediment accumulation rates than dividing nine samples across five cores. Samples were extracted at ~0.18 m intervals, to depths of 3.8, 4.7 and 5.0 m at the three sites, respectively, and laid-out top-to-bottom. The sediments were classified by colour and texture using the Munsell chart (Munsell, 1912). Since a limited number of samples could be dated, they were chosen using a step-wise approach, in three batches of three samples, with results informing the selection of subsequent samples.

The results of the exercise are given in Table 6.4, and include for each of the cores, sample depths, radiocarbon dates using Accelerometer Mass Spectrometry (AMS), and colour and texture descriptions. This study is concerned with recent changes in sedimentation (less than a hundred years), relative to the longer-term (hundreds to thousands of years), and samples chosen for dating are therefore associated with the shallower halves of the cores (based on the results of the test sample). Radiocarbon dating using AMS has dating limitations, with 95 pMC (percent Modern Carbon) referring to 1950, or 0 BP (Before Present).

To complement the radiocarbon dating, pollen and diatom analyses of the sediment samples in Table 6.4 were performed by Fitchett (2016).

Diatom species have specific environmental requirements, and consequently the proportional distribution of diatoms through a core has potential to inform about basic water quality at a point in time, for example water depth, temperature, salinity, pollutants, pH, conductivity and turbidity. Unfortunately, there were insufficient diatom valves in the three cores to facilitate statistical analysis.[342]

Pollen is produced in great quantities by flowering plants, has a highly resistant and is easily distinguishable structure in fossil form (Moore & Webb, 1978). Pollen grains can be identified to family level, and in some cases to specific genera (Faegri *et al.,* 1989; Birks & Birks, 2014). Transported readily by wind, pollen grains are representative of the local to regional environment, with a catchment radius of up to ~50 km (Jackson, 2012). Pollen can be used to assigning relative ages to sediments from the Permian (398 to 252 million years BP) but not for Holocene sediments (~11 000 years BP) because of the homogeneity of vegetation communities at that time. Where the date of introduction of an invasive species or agriculture is known, however, and where the spread of such vegetation occurs rapidly, the appearance of invasive pollen grains can be used to infer the age of the sediment (Van Leeuwen *et al.,* 2008). This is, however, an inaccurate means of determining age because the chances of contamination are high, and so such inferences should be made based on independently measured ages. Thus, for this study, sedimentation ages and rates could not be inferred from pollen or diatom communities in the sediment cores.

The pollen slides prepared from samples were more productive than the diatoms, and 31 of the 38 samples yielded sufficient pollen grains for analysis. The pollen grain distribution was limited, particularly for Cores 1 and 2 (Figure 6.14). The pollen sums for each of the three cores were dominated by undifferentiated *Poaceae* and *Asteraceae*. Although present, there was a notably low representation of wetland groups, including *Cyperaceae* and *Apiaceae*. There were considerable gaps within the stratigraphic record because many samples had insufficient pollen for counting, which limited the ability to make robust inferences, particularly about anthropogenically driven environmental change. Results of the pollen analyses are discussed in Section 6.2.3.2.

[342] A few of the samples had between one and ten diatom valves present per slide.

Table 6.4 AMS radio carbon dating of sediments sampled from three locations and from various depths within the Elephant Marsh, including other descriptions

Core C1				Core C2				Core C3			
Depth (mm)	Age (BP)	Munsell	Texture	Depth (mm)	Age (BP)	Munsell	Texture	Depth (mm)	Age (BP)	Munsell	Texture
350		dry		1170		5YR 4/4	clay	350		7.5YR 4/3	clay
370		dry		1600		5YR 4/4	clay	530		5YR 3/2	clay
425		dry		1785 (1)	(107 pMC)[343]	2.5 YR 4/4	clay	705		5YR 3/1	clay
635		dry		1905		2.5 YR 4/4	clay	850 (1)	933	7.5YR 3/2	clay
760		5YR 4/4	clay	2150 (2)	1028	10YR 4/6	clay	1005		5YR 4/3	clay
1020		7.5YR 3/3	clay	2250		10YR 5/3	clay	1180 (2)	1240	5YR 5/4	clay
1225 (1)[344]	583	2.5YR 3/3	clay	2280		10YR 5/3	clay	1375		7.5YR 5/8	sand/clay
1415		2.5YR 4/4	clay	2360		10YR 4/3	clay	1535 (3)	1338	7.5YR 5/6	sand/clay
1625 (2)	885	2.5YR 4/3	clay	2420 (3)	1445	10YR 5/3	clay	1702		7.5YR 5/4	sand/clay
2140		10YR 4/6	sand/clay	2450		10YR 5/3	clay	2022		7.5YR 5/4	sand/clay
2375		10YR 4/6	sand/clay	2500		10YR 4/6	clay	2282		7.5YR 5/4	sand/clay
2465		10YR 5/3	sand/clay	2650		10YR 4/4	clay	2697 (4)	1385	7.5YR 5/4	sand/clay
2608		10YR 4/4	clay	2874		10YR 4/4	clay	2762		7.5YR 5/4	sand/clay
2715		10YR 4/4	clay	2969		10YR 5/4	clay	3019		7.5YR 4/3	sand/clay
2775		10YR 4/6	clay	3099		10YR 4/4	clay	3109		10YR 5/6	sand/clay
2905		10YR 4/4	clay	3289		10YR 5/6	clay	3264		10YR 5/6	sand/clay
2995		10YR 5/6	clay	3419		10YR 5/8	clay	3429		10YR 5/4	sand/clay
3100		10YR 4/6	clay	3579		10YR 5/4	clay	3669		10YR 5/4	sand/clay
3450		10YR 5/6	clay	3714		10YR 4/4	clay	3814		10YR 5/4	sand/clay
3545		10YR 5/4	clay	3794		10YR 5/6	clay	3976		10YR 4/4	sand/clay
3645		2.5YR 5/6	sand	4157		10YR 4/4	clay	4301		10YR 4/4	sand/clay
3745		10YR 5/4	sand/clay	4325		10YR 5/3	clay	4451		10YR 4/4	sand/clay
3835		10YR 5/4	sand/clay	4475		10YR 5/4	clay				
				4560		10YR 4/4	clay				
				4745		10YR 4/4	clay				

343 Did not yield a useable radiocarbon date, so quoted as percent Modern Carbon (pMC); 95 pMC is the 0 BP reference (i.e., 1950)
344 '( )' refers to dated sample number for the core

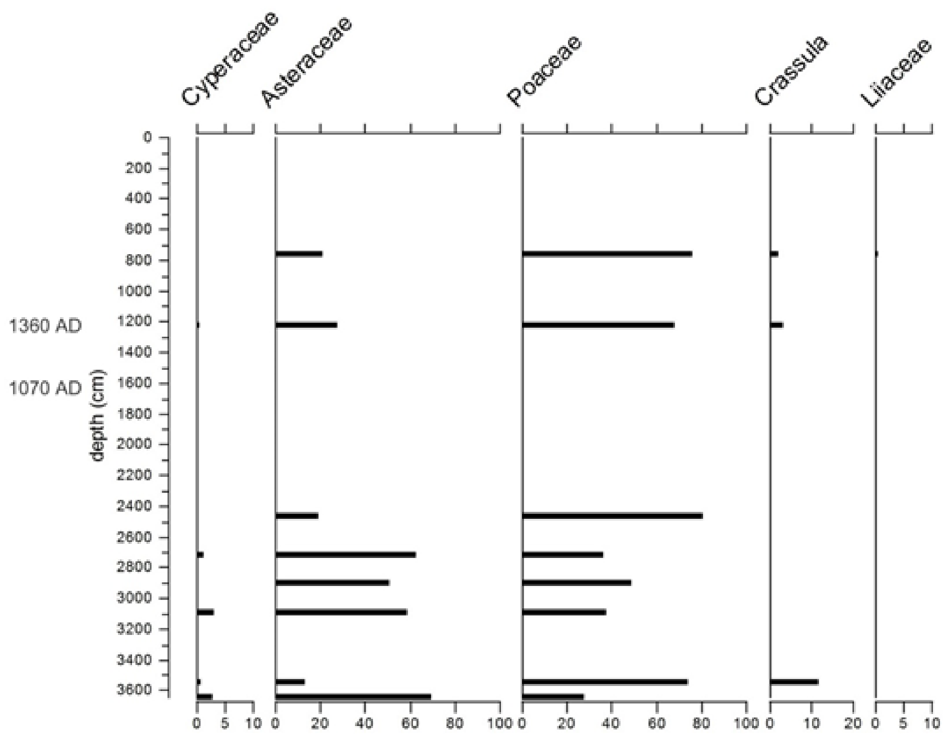

Figure 6.14 Stratigraphic pollen diagram for Core 1 (after Fitchett, 2016)

6.2.2.2 Suspended sediments and water chemistry

A monitoring programme was instituted over the one year period July 2015 to 2006 to provide data on changes in sediment concentrations and water chemistry across the extent of the Marsh. The original intention was to have two sampling locations, at the Chikwawa and Chiromo Bridges. The alternate Shire channel flowing through the breached railway embankment and re-routing of the Ruo River in early 2015 meant that the number of downstream sampling sites needed to be increased, and their locations revised. Four sites were chosen (refer to Figure 4.19): the Chikwawa Bridge; the Namichimba River before it enters Lake Tomaninjobi; the Ruo River upstream of the Marsh; the Shire River upstream of the Namichimba confluence (i.e., excluding the influence of the re-routed Ruo River's sediments). Suspended sediments were sampled using an integrated depth sampler, from the bridge at Chikwawa and from boats at the other three downstream locations. The results are tabulated in Appendix Table A1, and plotted in Figure 6.15. Water chemistry (or quality) samples were also collected at the same time and locations as the suspended sediment samples, and the results are also included in Appendix Table A1. Samples were processed by Bemlab (South Africa).[345]

A programme for event-based sampling of two high flows over a day each was planned to compliment the longer-term monthly-based sampling. In preparation of this, water levels were monitored daily at Kasinthula on the Shire River near Chikwawa from December 2015 to June 2016 as an early warning of the onset of events.[346] Unfortunately, there were no high flows suitable for sediment sampling in the 2015/2016 season as the wet season failed.

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[345] Opportunities for the processing water samples rather in Malawi were investigated with the Regional Irrigation and Water Development Officer, and with laboratory technicians in Blantyre (MoIWD), but was unfortunately unsuccessful due to costs and logistics

[346] Pre-selected or *ad hoc* dates for sampling events in this environment have little chance of success.

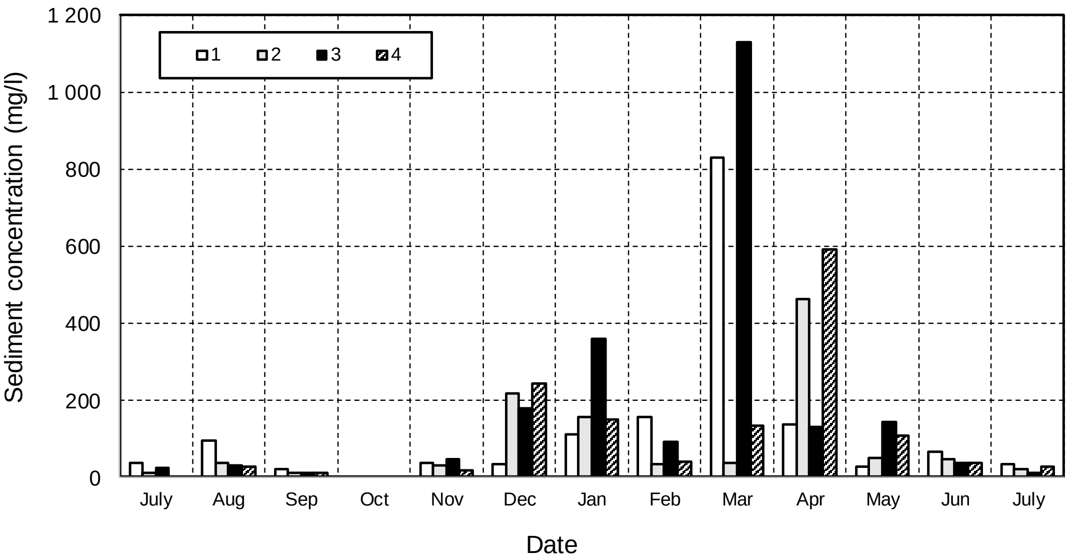

Figure 6.15 Monthly sediment concentrations over a year at four monitoring locations; 1: Chikwawa Bridge; 2: Namichimba River before it enters Lake Tomaninjobi; 3: the Ruo River upstream of the Marsh; 4: Shire River upstream of the Shire-Namichimba confluence (refer to Figure 4.19)

6.2.3 Discussion and summary

6.2.3.1 The southern region

Over the last hundred years or so, two events substantially influenced the morphological character of the southern region of the Elephant Marsh. The first was the building of the railway embankment and confinement of the Shire River to the Chiromo Bridge span (Figure 2.8 and Figure 2.11) and the second was the increase in sediment loads in the Ruo River.

As discussed in Chapter 4, it is likely that the backup effect of the railway embankment during high flows contributed substantially to morphological change in the southern region of the Marsh. The complex interactions between increased inundation,[347] enhanced sedimentation and vegetation response probably resulted in the present character of the southern and central/eastern Marsh, particularly the high proportion of shallow lakes and dominance of true marsh vegetation. Sedimentation of this downstream section can be inferred from the inset to Figure 6.7, which shows an elevated bed profile, reduced depths and a slightly increased water surface gradient[348] along the stretch between chainage 183 and 207 km.[349] The average depth along this 24 km stretch is 1.7 m,[350] compared to 4.1, 4.3 and 4.9 m along the lower Namichimba distributary,[351] the Namichimba-Shire confluence to Chiromo Bridge, and the alternate (right-bank) Shire channel,[352] respectively. Substantially deeper flows are associated with the lower Namichimba, and its less-turbid sediment-filtered water.

[347] resulting in increased depths with concomitantly reduced velocities
[348] compared to upstream
[349] Chiromo Bridge is at chainage 210 km, and the Namichimba-Shire confluence at 207.5 km
[350] at a discharge of ~190 m^3/s (September 2015)
[351] i.e., flowing from Lake Tomaninjobi to the Namichimba-Shire confluence
[352] i.e., flowing south-west to the breached railway embankment near Bangula

The Shire River in 2016 favours this right-bank channel as it is deeper and conveys more flow than the channel passing under Chiromo Bridge. This is evident in the near-horizontal water surface gradient between the diversion and Chiromo Bridge (inset to Figure 6.7). As noted in Chapter 4, the downcutting along this alternate channel should only be localised, but the effect of reduced (upstream) inundation may continue for some time into the future, depending on the level of equilibrium already achieved. Over longer periods, it is expected that the alternate Shire River channel will aggrade, given high sediment loads carried by the Shire, compounded by the Ruo's sediment now routed through the Marsh.

The sedimentation of the Shire River downstream of its (pre-2015) confluence with the Ruo is central to the existing morphology of the Elephant Marsh's southern region. This seems to be an odd statement, given that the Ruo's confluence (pre-2015 and from the earliest map dated 1859 in Figure 4.1) was downstream of Chiromo Bridge. In the hydrology chapter (Section 3.2.1.4), the backup-effect of the Ruo River's flows into the Marsh was discussed, regarding the hydrometric station at Chiromo Bridge. Changes in bed level downstream, due for example to sedimentation, affect (or control) water level (or stage) upstream. It follows then that changes in the bed level of the Shire River downstream of the Ruo confluence will affect water levels upstream - in this situation, the southern region of the marsh.

The first source of evidence indicating that this has taken place is the historic 1926 photograph of Chiromo Bridge (Figure 6.16), which captures a similar scene to that in Figure 2.8 taken eight years earlier, but is of better quality. Although the Chiromo Bridge was rebuilt in the mid-1900s (Figure 2.9), a left bank supporting structure from the earlier version remains today, and was used (as a datum) to estimate a stage difference of ~4 m between the 1926 and recent 2015 photographs. It is appreciated that the Shire was not flowing at the Ruo confluence during the dry season of in 1926,[353] whereas the Shire River's (total) flow on 1 October 2015 was ~190 m^3/s. The alternate channel (Figure 4.23u) carried most of this flow, however, with considerably less passing under Chiromo Bridge. The river stretch downstream of the bridge was too shallow for navigation in October 2015. Therefore, although the discharge in the recent photograph is higher, the difference in discharge cannot account for the estimated 4-m increase in water level for a channel width of ~50 m. The shallow depths[354] encountered downstream of the Ruo confluence direct attention to sedimentation of this channel bed.

There are three sources of information that indicate aggradation of the Shire River bed downstream of Chiromo Bridge since at least about the mid-1900s. The first of these are the gauge plate levels for the dry season - 2009 being the most recent available, which are ~5.0 m (corresponding to a discharge of 300 m^3/s, Figure 3.8). It is reasonable to expect that the gauge datum (i.e., zero level) would have been positioned at or close to the bed or low-flow water level. This is confirmed by periods in 1957 and 1965 which had the two lowest gauge plate readings on record[355] of 0.1 and 0.3 m, respectively. These correspond to the effect of the 'bund' in 1956 across the Shire River which prevented flow from Lake Malawi, and the construction of Kamuzu Barrage in 1965 (refer to Figure 1.9). This indicates that the Shire bed (at or downstream of Chiromo Bridge) has aggraded by roughly 4 m[356] in 56 years.

[353] Atkins (2012) data archive; original data source not given (station only opened mid-1900s)
[354] down to half a metre
[355] 1953 to 2009 (Table 3.3)
[356] 5 m corresponds to a discharge of roughly 300 m^3/s

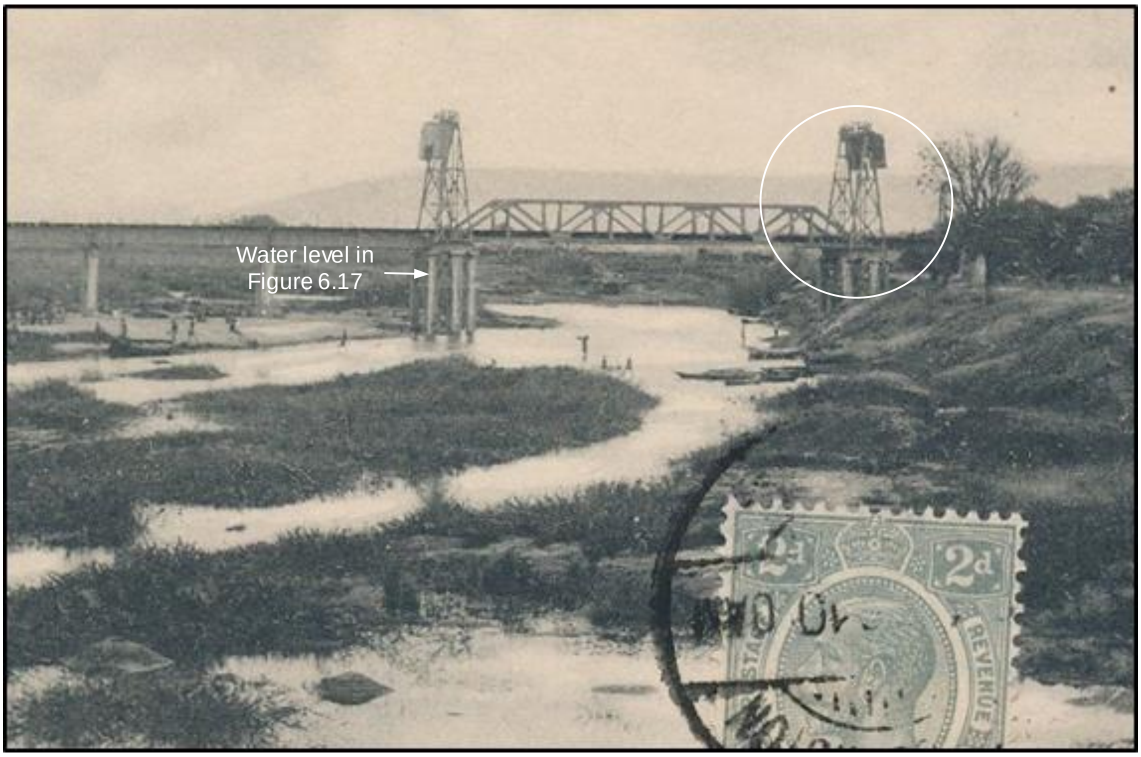

Figure 6.16 Historical 1926 photograph of the Chiromo Railway Bridge over the Shire River, facing upstream with the Thyolo Mountains in the distance; note circled left-bank structure.

Figure 6.17 Photograph (1 October 2015) of the Chiromo Bridge facing downstream; note circled left-bank structure

The results of the hydrodynamic modelling (Chapter 5) also suggest sedimentation of the river bed downstream of the Shire-Ruo confluence. In the modelling, a rating function defines the relationship between water level and discharge (stage-discharge or rating) below the confluence, and is based on existing conditions. The stage/gauge plate plot in Figure 5.7 shows reasonable correspondence between modelled stages and gauge observations for recent times (since about 2000), but with apparent errors before 1999. These are not inaccuracies, but a reflection of temporal changes in the downstream rating relationship due to sedimentation and breaching of the embankment. By comparing modelled stages with observed gauge plate levels over time, and taking account of the breached railway embankment in the hydrodynamic modelling, changes in bed level can be deduced. These are plotted in Figure 6.18 for the modelling period 1976 to 2009, relative to a zero datum which establishes the more-recent (2009) situation. Similar temporal variations occur at Chiwawa and

Chiromo, but with a higher rate of increase at Chiromo in the mid-to-late 1990s. The plot for the Chiromo Station shows a shift of ~3.75 m since the early 1980s. Correspondence between sedimentation and historic flows (refer to Figure 3.8) are well correlated: negative gradients (i.e., erosion) are associated with periods of increasing flow; positive gradients (i.e., sedimentation) correspond with periods of reducing flow, or follow periods of reduced flow. The graph for Chikwawa indicates a net (marginal) accumulation of less than half a metre over the 33-year period. After the high flows of the late-1970s, the downstream bed levels (which affect upstream water levels) were much lower (~1.5 m below more-recent levels).

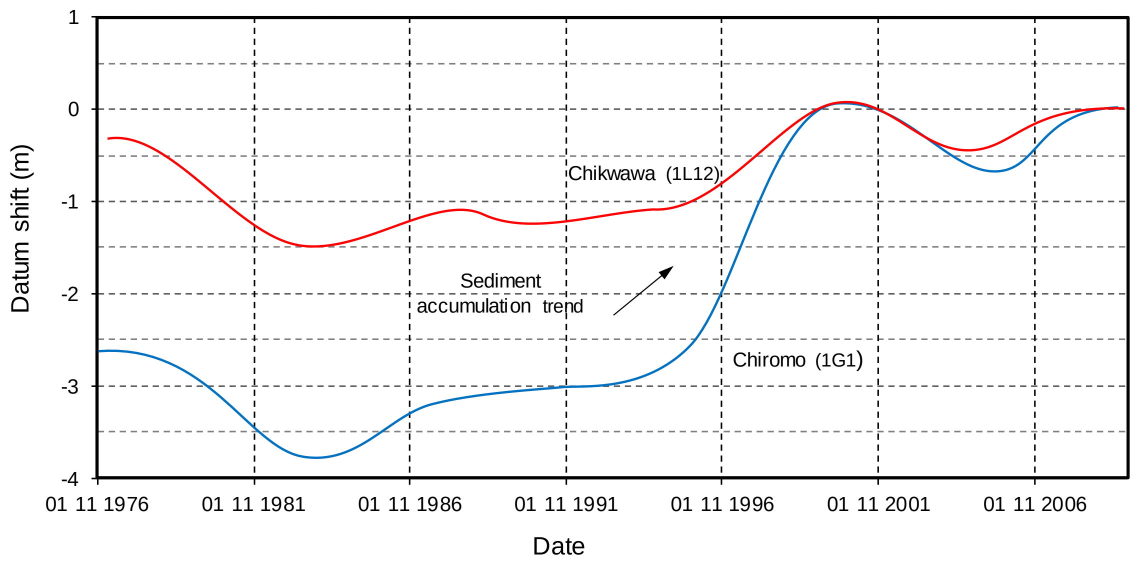

Figure 6.18 Datum-shifts (smoothened) at the Chikwawa and Chiromo hydrometric stations over the period 1976 to 2009, derived from differences between observed water levels and modelled stages using the existing physical template;[357] an increase in datum over time infers sediment accumulation

Sedimentation of the Shire River due to sediment transported by the Ruo is considered largely responsible for the substantial datum shift at Chiromo over the 33-year period (Figure 6.18), which is not as evident in the more-dampened behaviour at Chikwawa. To support this, attention was directed to the gauge records from the Sinoya Station, which were used to synthesize discharge time-series for the Ruo River (refer to Section 3.4.2.1). Descriptions of sedimentation at hydrometric stations along the Ruo River are given in the station history (refer to Section 3.2.2) but the water-level plot in Figure 3.9 illustrates the situation well: the bed has aggraded by 6.4 m over the 42-year record from 1962 to 2004. It is reasonable to expect that the historic sedimentation evident along the lower Ruo has also occurred below the Shire confluence. Two periods of increased aggradation (i.e., high sediment loads) are noted from Figure 3.9: 1984 to 1989, and 1996 to 1999. These periods correspond with increased rates of sedimentation as shown in Figure 6.18. The first period was associated with high flows in the Shire River at Chikwawa (average of 593 m^3/s), whereas the second experienced noticeably lower flows (average of 207 m^3/s). It is sensible, therefore, that the latter period displays a higher rate of sedimentation in Figure 6.18.

These findings also provide insights regarding the breaching of the railway embankment in the 1990s, and the Ruo River's change of course in 2015. The evidence suggests that three activities have been

[357] for Chiromo, a no-breach situation is included for simulation before the late 1990s

central to these events: the damming-effect of the embankment over more than a century; substantially higher (compared to natural) sediment loads from upstream catchments over many decades; and the change in the hydrological flow regime in the early 1990s. These have acted over different time scales to substantially aggrade the lower Ruo and Shire River below their confluence, and promote sedimentation in the southern region of the Marsh. This contributed to (if not resulted in) the breaching of the railway embankment in the 1990s. The Shire River subsequently developed a right-bank distributary channel through one of the breaches, as an alternate to the aggraded (historical) channel below Chiromo Bridge. Similarly, with a reduced conveyance, the Ruo River overtopped its levees and developed an alternate channel through the Marsh. As mentioned in Chapter 2, there have been considerations of engineering the Ruo River to return it to its pre-2015 course. A recent media publication[358] from September 2016 confirms that this is still current:
"*As government says [it] will not complete the dragging of Ruo river in Nsanje district this year which changed its original course during the January 2015 floods, Nsanje full council want it done this year. This comes after Disaster Management Affairs (DoDMA) Public Relations Officer Jeremiah Mphande in an interview said government requires ample time to work on the River. Mphande, said DoDMA has yet to source funds for the work which he says will be done after the submission of the design of the river training project*."

Based on the inferences above, it is questionable whether an endeavour to 'train' the river back into its historic (active channel) course, without drastically also reducing sediment loads produced in the upstream catchment, would be successful in the long term. Particularly given that projected climate futures (Chapter 3) are predicted to exacerbate the soil loss and extreme weather conditions.

6.2.3.2 Radiocarbon dating and pollen analyses of sediment cores

The radiocarbon AMS dating of samples from the three cores has provided useful data on long-term sediment accumulations as well as the likelihood of more-recent changes - the latter based on the assumptions described below. The long-term average rates of sedimentation are reasonably consistent, with 1.7 mm/yr over the last 950 years; 1.6 mm/yr over the last 1 510 years; 1.1 to 1.9 mm/yr over the last 1 403 to 1 450 years; and 1.4 mm/yr over the last 6 415 years, for Cores 1 to 3 and the test sample, respectively. These are based on the dates corresponding to the deepest samples and given that presently, sedimentation is active at all three locations.[359] For Core 3, there is an apparent discrepancy between the depth-dates for the two deepest samples (i.e., 3 and 4) compared to shallower samples, since the dates are similar for these two samples which are over a metre apart. This site is in the southern region of the Marsh and close to the Shire River's historic course,[360] and it is likely therefore that it has been affected by recent channel change. For this reason, a range of average sediment accumulation is given, based on the two deepest samples.

Considering the depth-dates in Table 6.4 in more detail, to exclude recent anthropogenic influences:

- for Core 1, the average rate of accumulation was 1.3 mm/yr between AD 1065 and 1367;
- for Core 2, a date could not be returned for the shallowest sample (107pMC), but it can be placed at no older than ~the year 1850 (i.e., 100 BP); consequently, the average rates were between 0.4 and 0.6 mm/yr, between AD 505 to 1850, and;
- for Core 3, aggradation is estimated at 1.7 mm/yr between AD 612 and 1017 (using Samples 1 and 3).

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[358] http://www.nyasatimes.com/nsanje-council-wants-ruo-river-back-original-course/#sthash.yUhPzhBj.dpuf
[359] i.e., zero depth relates to a date of ~-65 BP (2015 less 1950)
[360] Pre-1970s and dating back to at least the mid-1800s (refer to Chapter 4); locating a downstream site was difficult, since boat failure dictated that it needed to be accessed overland

The two lower rates obtained for Core 2 (from 3 samples), while reasonably close, are much lower than those at upstream and downstream sites. A possible reason is the recent (late-1900s) change in course of the Shire River through the Marsh, from its more distant (relative to Site 2) south-western course, which may have existed for many hundreds of years. High flows are associated with changes in channel planform (e.g., Ruo River during the 2015 floods). Based on Lake Malawi water levels (Figure 2.17), the (recent) high flows of the late-1900s are inferred to also have occurred in the late 1800s,[361] and during three periods over the past thousand years or so. The extreme changes in landcover since (at least) the 1970s provide good reason to expect that the more-recent high flow period was associated with sediment loads far exceeding those of previous wet periods when the upstream catchments were more intact. Alluvial rivers with high flows and sediment loads are conducive to changes in channel planform geometry, whereas high flows associated with low sediment loads can lead to channelisation (i.e., a more stable planform), through the entrainment (erosion) of bed material resulting in incision. Thus, the Shire River's historic south-western course through the Elephant Marsh (i.e., distant from Site C2) may have existed for some time (i.e., a reasonably stable planform geometry). This is supported to some degree by Beville *et al.*'s 1867 sketch map[362] (Figure 4.2), which indicates a "*great forest of palm trees*"[363] extending from Nsua Island, through the present marsh (i.e., close to where Site C2 is located) to north of Lake Tomaninjobi where they grow today (refer to Figure 2.4). Palm trees indicate the transition between marsh and terrestrial areas at that time, and the establishment of a "*great forest*" suggests a time frame of many hundreds of years.[364] Also, the lower rates of accumulation at Site C2 (165 to 1510 years ago) suggest that the 1860's south-western course for the Shire River may have existed for at least a few hundred years.

Considering average rates of accumulation for the surface layer, values of 1.9, 10.8 and 1.0 mm/yr are calculated for the three cores over the last 648, 165, and 998 years, respectively. In terms of their longitudinal locations and local conditions: a lower rate at Site C3 compared to Site C1 could reflect its downstream position, given an expected reduction in sediment concentration with distance downstream. The substantially higher (order of magnitude) rate indicated for Site C2 (i.e. 10.8 mm/yr) is over a much more recent time frame (i.e., 165 years), and is likely due to the large-scale deforestation and associated high rates of soil loss that have occurred over the last half century or so, which was highlighted in Section 6.1.

Based on this, it is informative to split the surface layers into two periods: the most recent 50 years, and the balance from the dating of the shallowest samples. Estimates of accumulation over the last 50 years can then be estimated by using both the average rates (i.e., from the shallowest samples that include both pre- and anthropogenic influences) and longer-term rates[365] from the deeper layers below (i.e., pre-anthropogenic influences). For example, the rate of aggradation at C2 over the last 50 years is estimated as follows:

[361] during Livingstone's expeditions up the Shire River
[362] when more accurately geo-refenced using Johnston's 1893 map
[363] Livingston and Livingston, 1893
[364] Borassus palms are very slow growing and flowering possibly does not occur until the tree is 30 or 40 years old and as much as 7 m in height (Palgrave and Palgrave, 2002)
[365] *viz*. 1.3, 0.4 and 1.7 mm/yr for the three cores, respectively.

$$\frac{(165 * 10.8) - ((165 - 50) * 0.5)}{50}$$

Equation 6.1

where 0.5 is the average pre-anthropogenic rate in the range 0.4 to 0.6 mm/yr.

For C1 and C2 (i.e., Equation 6.1), this gives rates for the last 50 years of ~10 and 34 mm/yr, which are closer to each other,[366] and substantially higher than both pre-anthropogenic and long-term averages of 1.3 and 1.7 mm/yr for C1, and 0.4 to 0.6 and 1.6 for C2, respectively. For C3, the average surface rate (1.0 mm/yr) is less than the pre-anthropogenic rate (~1.7 mm/yr), indicating an apparent reduction in the recent rate of aggradation. As mentioned previously, this site is in a region of the Marsh associated with recent[367] channel activity, which could be the cause of apparent inconsistencies when relating sample depth to rate of accumulation.

The results from radiocarbon dating support the inferences from secondary data presented previously (*viz*. landcover change, modelling of soil losses, sedimentation of reservoirs, and photographic evidence of high sediment concentrations). The average rates of sediment accumulation, pre-anthropogenic influence, were in the range 0.4 to 0.6 mm/yr, for a site located distant,[368] and 1.3 to 1.7 mm/yr for two sites in closer proximity,[369] to the Shire River's course. If recent changes in sedimentation due to human activities are taken to apply to the last 50 years or so, then rates are indicated to have increased by at least an order of magnitude (*viz*. 10 to 34 mm/yr).

For Core 1, the absence of pollen between 1.2 to 2.4 m coincides with the Little Ice Age, which may have resulted in conditions too cold for abundant plant growth, or extensive drying of the wetland (Tyson *et al.,* 2000). The floral families are consistent with wetland environments, but there is a low relative abundance of wetland groups. Statistically significant variations between *Poaceae* and *Asteraceae* most likely represent fluctuations between relatively dry and wet conditions, respectively. Dry conditions would have resulted in a landscape dominated by grasses and succulents, while during wetter periods there would likely have been greater surface water availability, sustaining larger populations of *Cyperaceae*.

Fluctuations between wet and dry conditions are less apparent for Core 2. This seems to corroborate the previous conclusion (based on rates of sediment accumulation for pre-anthropogenic influence and from historical sketch maps), suggesting that Site C2 was for some time prior to the 1860s, located on the periphery of the Marsh. There is also an indication of a discrete dry period at 3.7 m depth, but it is deeper than the deepest-dated sample from a depth of 2.4 m.

Core 3 reflects greater fossil pollen taxa diversity than is apparent for the other two cores, being more representative of sequences expected for wetland environments. The relative changes between *Poaceae* and *Asteraceae* are again broadly interpreted to represent cycles between dry and wet conditions.

The purpose of the diatom and pollen analyses of Fitchett (2016) was to assess whether the effect of human activities, specifically changes in rates of sediment accumulation, could be ascertained from the paleo record. Unfortunately, the fossil pollen record does not provide evidence of this, with limitations being *inter alia* sampling resolution and the small diversity of plant taxa captured in the fossil record, as well as the absence of well-preserved diatoms. The interpretations of Fitchett (2016),

[366] than 1.9 and 10.8 mm/yr for the entire surface layers at C1 and C2
[367] over the past 150 years
[368] ~6 km
[369] less than 1 km

although restricted to broad shifts between relatively wet and dry conditions, are useful as they support the inferred hydrological behaviour of the Marsh from long-term fluctuations of Lake Malawi water level (Figure 2.17), which suggest frequent periods of low flow in the Shire River. The interpretations from the pollen analyses are also corroborated by historic descriptions of conditions during dry periods, which noted a different, and non-wetland, floral community during dry periods (Chapter 2).

6.2.3.3 Suspended sediments

While it is difficult to draw detailed conclusions from the results of the monthly sampling of suspended sediments (Figure 6.15), a few general findings are evident. The first of these is the obvious overall increase in sediment concentration in the wet season. Given that the wet season failed to produce a general increase in flows or events, increases in concentration did not occur throughout the wet season and nor at all sites. During the dry season, the sediment-filtering of the Marsh is evident, with average concentrations halved between the upstream (S1 at Chikwawa) and downstream sites (S2 and S4). The average concentrations at S1 were 48 mg/l, reducing to between 20 and 26 mg/l downstream. Some samples during the dry months indicate as much as a four-fold upstream-downstream reduction in sediment concentration.

Sediment-filtering of the Marsh is also indicated from samples taken in the wet season, where reductions may be higher than an order or magnitude (*viz*. March). For some monthly samples in the wet season, however, the upstream-downstream relations seem counter-intuitive, indicating increases in downstream (for both sites) suspended sediment concentrations (*viz*. December, January, April and May). This is attributed to sediment contributions from intervening tributaries (i.e., between Chikwawa (S1) and the two downstream sampling locations (S2 and S4)). The effect of this would be more pronounced when Shire River flows are low (Figure 6.19). Such a situation was observed in December 2015, when the Mwanza River flowed strongly for only a few days, carrying high sediment loads.

During the dry season, suspended sediment concentrations in the Ruo River were lower than in the Shire (at Chikwawa), and similar to those measured in the Marsh (i.e., at S2 and S4). Unfortunately, the failed 2015/16 wet season thwarted event-related data collection. It is reasonable to expect, however, that concentrations in both the Shire and Ruo Rivers flowing into the Marsh exceed 1000 mg/l during high flows and floods. During the study's wet season, sediment concentrations in the Marsh exceeded 200 mg/l in two of the months.

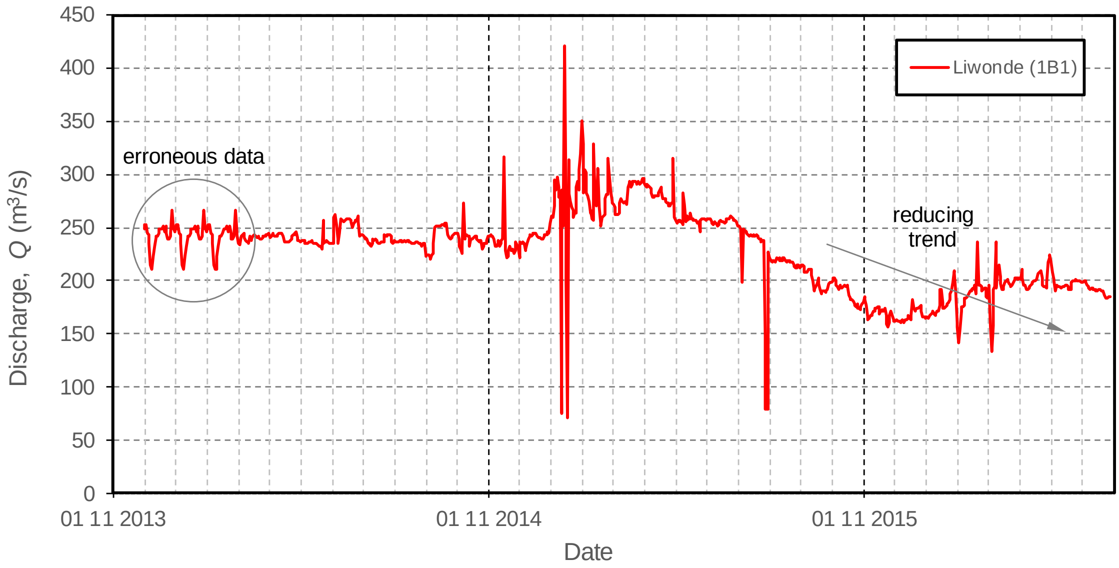

Figure 6.19 Daily discharge time-series for the hydrometric station at Liwonde, showing a reducing trend since 2015[370]

6.3 Summary

Extreme human pressures on the Malawian landscape can be traced back to at least the early part of the 20th century (Topham, 1936; Pike, 1968a) with clearing of woodland for cultivation dating back to at least the mid-1900s. Deforestation, land fragmentation, cultivation of wetlands and rapid increase in human settlements have produced substantially increased runoff, elevated flood peaks with more-rapid catchment response, and reduced groundwater recharge and concomitant dry season flows. Because of this, the rate of soil loss is now roughly double rate of soil formation. Projections are that climate change will further exacerbate this dire situation and that erosivity will increase by up to 17% by 2050.

The Elephant Marsh is a natural depositional zone along the Shire River, within a rift valley setting. The southern and central/eastern regions of the Marsh are the most diverse in terms of wetland morphology and associated habitat, and contains almost all the shallow lakes and indigenous marsh vegetation. These areas are also efficient in trapping sediment entering the Marsh, with between a 2 and 4 times reduction in sediment concentration measured for the dry season.

The notion that the Elephant Marsh has experienced regular and prolonged periods of drying out, following by prolonged periods of greater flooding than it currently experiences, is supported by pollen analyses linked to radiocarbon dating of Marsh sediments. The construction of the railway embankment and the high sediment loads entering the Shire from the Ruo River have greatly influenced the Marsh’s morphology. Sediment loads have substantially aggraded the lower Ruo and Shire River below their confluence. This and the embankment have promoted sedimentation in the southern region of the Marsh. This, in turn, supported the breaching of the railway embankment in the 1990s; the development of an alternate right-bank Shire channel, and; the re-routing of the Ruo River into the Marsh through Lake Tomaninjobi. Establishment of the alternate right-bank channel subsequently lowered water levels upstream, and together with decreasing Shire River flows, resulted

[370] gauge plate data sourced from MoIWD; the repeated time-series over three months commencing December 2013 is erroneous

in lower depths in lakes, which are evident in Lake Bangula. The rerouting of the Ruo has exacerbated the situation, already having deposited large quantities of sediment into Lake Tomaninjobi.

Long-term resilience of the Marsh hinges on minimising sediment delivery to these areas, particularly the lakes, and on ensuring adequate depths (> 1m)[371] encroachment by aquatic and riparian vegetation that favours shallower depths. The rate of current sedimentation in floodplain/marsh areas is estimated in the range ~10 to 34 mm/yr, which is 10 to 20 times higher than before human-influences. This is accompanied by channel bed aggradation, which since the early 1980s has been about 1.5 and 3.75 m near the Chikwawa and Chiromo Bridges, respectively.

The final chapter contextualises the Elephant Marsh relative to other wetlands across the continent, and regionally, and summarises its past behaviour, trends, and perceived future resilience.

[371] e.g., phragmites grows where depths do not exceed 1.3 m for longer than 10 days, or 1.18 m for 30 days per annum (Gaudet, 1992); depths less than 1.5 m support rooted papyrus (Sutcliffe, 1974).

7 Hydromorphological functioning of the Marsh: contextualisation, past behaviour and future resilience

7.1 Contextualising the Elephant Marsh relative to other wetlands

The most extensive wetlands on the African continent are periodically-flooded ecosystems of lakes and rivers situated between latitudes 15 and 20 °S (Schuyt, 2005) and include:

- wetlands adjacent to the Nile, Niger, Zaire and Zambezi Rivers;
- Lake Chad;
- wetlands of the Niger Delta in Mali;
- the Rift Valley lakes (Tanganyika, Victoria, Malawi, Turkana, Mweru and Albert);
- the Sudd in Southern Sudan and Ethiopia, and;
- the Okavango Delta in Botswana.

There are many different wetland classifications. One of the simpler ones is that of Rogers (1995), who describes four wetland types:

- alluvial lowlands, which are fringing floodplains, inner deltas and coastal delta floodplains;
- small valleys, which are headwater lowlands and small overflow valleys;
- lakeshore wetlands, and;
- depressions, which are wetlands in river and lake systems and isolated topographical lows.

There are three vegetation units that may occur in any of the wetland types:

- periodically-flooded ecosystems, such as flooded forests, flooded grasslands and seasonally inundated shallow lakes and water bodies;
- permanently- or periodically-flooded swamps and marshes, such as sedge and/or reed swamps, swamp forests and peat swamps, and;
- permanent shallow lakes and water bodies, such as natural ponds, oxbow lakes and lagoons.

The most common wetlands in Africa are floodplain wetlands (alluvial lowlands) and wetlands associated with lakes (depressions; van Dam 2011). The Elephant Marsh comprises both these types; it is a floodplain wetland with seasonal and permanent shallow lakes and water bodies, and comprises permanently flooded sedge (papyrus) and reed (common reed and bulrushes) marshes. Floodplain wetlands experience short-duration flooding at an annual, or longer, frequency. The volume, timing and character of flow (and sediment transport) through the river, and the geological character and history of the landscape, create site specific fluctuations in surface and groundwater flow. This varied fluvial geomorphology of the marsh influences plant growth characteristics and results in this extremely variable vegetation (Rogers, 1995).

As with other floodplain wetlands, sedimentation causes constant change in wetland structure as channels aggrade and scour in response to changes in flow and sediment regimes (McCarthy *et al.* 1986). Sedimentation processes may lead to a decline in flow velocity through direct channel aggradation, which may then be accompanied by secondary encroachment of papyrus from the channel margins into the channel (McCarthy *et al.,* 1998). Encroaching papyrus rhizomes, culms and umbels further constrict the channel, forming a tangled debris mat (called a sudd) that breaks off and floats into the channel (Ellery *et al.*, 1995). The growth of hippo grass (*Vossia cuspidata*) is favoured in this situation and further constricts the channel, thus trapping debris mats and further enabling papyrus encroachment (McCarthy, 1992). A debris dam may form that diverts flow beneath the blockage, scouring a new depression in the channel bed that will increase flow to the surrounding marsh around the failing channel, or into hippo trails that become enlarged and form new channels (Ellery *et al.*, 2000).

The papyrus (*Cyperus papyrus*) marsh component of these floodplain wetlands are considered extremely important for ecosystem services, flood attenuation and sediment trapping, provision of natural resources and habitat for specialist birds and semi-aquatic mammals (van Dam, 2011). This is, in part, due to their permanent inundation, as this reduces the extent to which cultivation takes place and thus maintains their role as refugia for aquatic and semi-aquatic organisms. Ideal conditions for papyrus wetlands include mildly sloping valleys and floodplains, permanently waterlogged soil, intermediate current velocities and wave action (Beadle, 1974 and Thompson, 1976 as cited by van Dam 2011).

Papyrus marshes are extensive in sub-Saharan Africa, although exact geographical extents are not known since their areal extent changes seasonally and between years (van Dam, 2014). The largest estimated areas of papyrus marsh (after Hughes and Hughes, 1992) occur in the Sudd wetland (3 900 km^2), Lake Chad (240 km^2), Upemba Basin in the Democratic Republic of Congo (1 100 km^2) and the Okavango Delta (2 500 km^2). The total area of permanently inundated papyrus at Lake Victoria, in Uganda, western Kenya, eastern Democratic Republic of Congo, northwest Tanzania, Rwanda and Burundi at the turn of the century was 1 532 km^2. Lake Chad is the westernmost significant occurrence since papyrus marsh is rare in West Africa, although it is reported in Nigeria, Benin, Guinea, Cote d'Ivoire, Benin and Gambia (van Dam, 2011).

Hughes and Hughes (1992) estimated the total area of papyrus marsh In East Africa to be 40 000 km^2. These marshes occur in river valleys and on lake edges and support the livelihoods of millions of people (van Dam, 2014). The Elephant Marsh is located here in the Zambezi River Basin system that flows through the countries of Angola, Zambia, Zimbabwe, Malawi, Botswana, Namibia and Mozambique. The occurrence and extent of papyrus wetlands in the Zambezi River Basin is shown in Table 7.1 (Schuyt, 2005). The Elephant Marsh is the second smallest[372] after the Linyati/Chobe River swamps, and is afforded no protection. The only other swamp in the Zambezi River Basin with an unprotected status is the Lukanga Swamp in Zambia. The Elephant Marsh is the largest wetland Malawi,[373] and with a large area of papyrus marsh habitat (Table 7.2).

Permanent and seasonal inundation creates zonation in papyrus marshes. In the permanent zone papyrus is extremely productive and outcompetes most other species resulting in almost pure stands of papyrus. Plant diversity is low due to shading and low dissolved oxygen levels and low pH, resulting from high loads of decaying organic matter. Other species adapted to these conditions include *Miscanthus junceus, Phragmites australis, Typha domingensis* and *Vossia cuspidata.* Drying and papyrus removal leads to an increase in plant diversity as more drought tolerant species can compete. These drier periods allow access for livelihoods activities (agriculture, livestock herding and vegetation harvesting). Papyrus vegetation recovers during the wet season when the dry zone is re-flooded, unless permanent changes are made to the vegetation, water or soils by constructing channels or removing rhizomes. Over a longer time-frame, the persistence of papyrus wetlands is strongly influenced by the effects of climate change (natural and anthropogenic) on river flows, and other direct human impacts that degrade land in the catchments upstream and in the Marsh.

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[372] of the ten largest in the Zambezi River Basin
[373] apart from Lake Malawi, which is a wetland by certain definitions

Table 7.1 Wetlands of the Zambezi River basin dominated by papyrus (after Hughes and Hughes, 1992, and Schuyt, 2005)

Name	Country	Area (km²)	Vegetation habitats present	Protection status (1992)
Cuando (Caprivi)	Angola/ Namibia	5947	Riparian reed swamps, lakes, marsh	Luiana Partial Reserve
Linyati swamp (Caprivi)		2000	Sedge swamp, fringing reeds beds and grassland, riverine forest, lakes	Partially in Caprivi Game Reserve, much unprotected
Okavango Delta	Botswana	2500	Channels, sedge swamp, fringing reeds, lakes	Moreni Wildlife Reserve
Linyati/Chobe Rivers		200	Swampy floodplains, reed swamps and backwater lakes, riverine forest	Chobe Forest Reserve, Chobe National Park, Kasane Forest Reserve
Luena flats	Zambia	1100	Sedge swamps, fringing reeds and narrow grass floodplains	Unknown
Barotse floodplain		9000	Channels, seasonally inundated floodplain, connected and isolated lakes, secondary channels, sedge swamps	West Zambezi Game Management Park
Busanga (Kafue)		2000	Sedge swamp	Kafue National Park
Lukanga (Kafue)		2500	Sedge swamp	No protection
Kafue flats		6500	Seasonally flooded grasslands, oxbow lakes, abandoned channels, swamp forest, seasonally inundated woodland, papyrus and reed swamps.	Kafue National Park
Luangwa		2500	Swamp forest, riparian forest, oxbow lakes, seasonally inundated floodplain, papyrus and reed swamps	North and South Luangwa Parks, Luambe National Park
Elephant Marsh	Malawi	512	See table below	Unprotected

Table 7.2 Papyrus wetlands in Malawi

Name	Location	Area (km²)	Vegetation habitats present	Protection status (1992)
Elephant Marsh	Shire/Namichimba split to Chiromo	512	Papyrus and reed swamps, lakes, seasonally inundated floodplain.	Unprotected
Vwaza Marsh	South of Katumbi, Lewewe River	400	Marshes, reed/grass/sedge swamps, floodplain, dambos, riparian swamp, grassland	Vwaza Marsh Game Reserve
Marshes of the Lilongwe Plain	Lilongwe Plain	>350	Woodlands and marshes	Unprotected
Lake Molombe	Middle Shire River	300	Marshes, riparian and floodplain vegetation, gallery forest	Liwonde National Park
Nkhotakota Lakeshore Lowlands	Lake Malawi	200	Unaka Lagoon, Bana Swamp, Dzedza Swamp, various marshes	Unprotected
Ndinde Marsh	Nsanje	200[374]	Swampland, lakes, floodplain	Unprotected
Salima Lakeshore Plain	Lake Malawi	165	Marshes and the swampy delta of the Lilongwe River	Unprotected

[374] the Ndinde Marsh falls in Malawi and Mozambique

Name	Location	Area (km^2)	Vegetation habitats present	Protection status (1992)
Marshes of Kasungu Plain & the Bua River	Kasungu Plain	>100	Grassy swamps, floodplain, marshes, dambos, riparian swamps.	Kasungu National Park, Nkhotakota Game Reserve
Marshes of Fort Hill Plain	South of Ruwenya Hills	100	Woodland and marshes	Unprotected
Marshes of Ruwenya Hills	Northwest Malawi	>10	Grass and reed swamps	Unprotected
Wetlands of the South Rukuru River	Western Zambian border	>10	Marshes	Nyika National Park
Karonga Lakeshore Plain	Lake Malawi	>10	Swamps, dambos and marshes	Unprotected

7.2 Past behaviour and trends

The information and findings presented in the preceding chapters give insights to, and provide evidence of hydromorphological changes in the Elephant Marsh over the past 157 years, and likely changes over much longer time frames. The purpose of this section is to integrate these to provide a chronological synthesis of the Marsh's hydromorphic behaviour over the last one-and-a-half centuries, and to describe more-recent trends.

The earliest (circa 1859) documented descriptions and maps of the Marsh are from Livingstone's expeditions along the Shire River in search of a gateway to central Africa's interior. From these and other later 19th century accounts, the following picture emerges of the river and Marsh during the relatively high flows of the mid-to-late 1800s: a braided channel planform; a better-defined, less distributed and wider main-stem channel than exists today - certainly in the central region of the Marsh (*viz*. Figure 4.23s); a south-westerly location relative to its current position (river and marsh); a less expansive marsh that extended from Alumenda Village in the north to the Ruo confluence in the south; few, if any, lagoons or lakes; extensive cultivation of floodplains, islands, and areas adjacent to the river channel upstream of Alumenda; and strong seasonal fluctuations of water depth and area of inundation, with channel depths as shallow as ~1 m during the dry season.

Before describing subsequent changes, it is instructive to consider conditions over many thousands of years, to give a longer historical perspective. Flows through the Marsh are largely dependent on water levels in Lake Malawi, and there is irrefutable evidence that outflow into the Shire River terminated twice in the last two centuries, and likely four times in the past 1 200 years. The effect of the most recent occurrence in the early 1900s is described below, and a prior (1700/1800s) occurrence was of even longer duration. Given that a fall of a few metres in lake level terminates outflow to the Shire River: longer-term changes indicate decreases in lake level of up to ~100 m over the past 20 000 years, and more substantial fluctuations (up to 550 m) occurred between 60 000 and 145 000 years ago. Pollen data from sediment cores extracted from the Marsh are dated at up to 1 500 years, and interpretation of these corroborates these broad shifts between dry and wet conditions.

Moving ahead in time again to the 19th century, falling lake levels (and flows) from about 1880 resulted in depths of less than half a metre during the winter dry season (circa 1893), while those during summer exceeded 1 m. During the late 1890s, the 'Marsh' is described as a district of great

grassy flats, occasionally inundated, but typically a dry level stretch of prairie[375] with scattered pools (Johnston, 1897). From the pollen analyses, a similar picture is described for dry periods (though in the more distant past), with a landscape dominated by grasses and succulents. The cessation of flow in the upper Shire River in the early 1900s resulted in a landscape very different to that of today. Accounts from this period describe no visible indications of a marsh and no trace of water, with large areas previously occupied by swamp being cultivated (Richards, 1954; Maxwell, 1954). This gives an interesting perspective on the history of cultivation in the Marsh, which differs from the following account (World Bank, 2012):
"*Traditional Authorities were clear that there was very little farming in the Elephant Marshes until a severe drought in 1991, since which time droughts have become more frequent and rainfall much more difficult to predict. The drought of 1991 forced farmers into the marshes in search of soil moisture and now many of the islands in the area are cultivated each dry season*."

Although drought conditions of the early 1990s "*forced farmers into the marshes"*, it needs to be recognised that low lake levels and associated low flows in the Shire River, and reduced inundation, exposed lands well suited to cultivation. These conditions thus provided farmers with an opportunity to plant. Concerning cultivation during the early 1990s, however, there are references to recessional agriculture, since cultivated areas were flooded by tributaries during wet seasons. Accounts and evidence of people wading and driving vehicles across the Shire River are further testimony to the dry conditions in the river and marsh, at that time.

The early 20th century also heralded in the construction of the infamous Chiromo Railway Bridge, and its elevated flanking embankment. This structure, now over a century old, is considered to have contributed substantially to the present morphology of the southern marsh,[376] which contains a large proportion of the Marsh's shallow lakes or lagoons. Another influence on the morphology has been the sedimentation of the Shire below Chiromo Bridge, which is attributed to high sediment loads transported over many decades by the Ruo. This activity (bridge building) and process (sedimentation of the Shire) have enhanced inundation, sedimentation and vegetation response in the southern marsh. They are also considered to have resulted in, or at least largely contributed to, breaching of the railway embankment, and more recently, the Ruo's re-routing through the Marsh in 2015.

Flows from Lake Malawi into the upstream Shire River commenced once again in about 1933, and the earliest maps of the Marsh illustrate conditions from about mid-century (e.g., Figure 4.9). Maps were often based on aerial photography spanning many decades, making assessments of temporal change difficult. Notwithstanding this, during the period between about 1935 and 1975, hydrological conditions were, on average, comparable to those of the mid-to-late 1800s. Topographical maps from this period show the southern lakes, but with very different spatial coverages, and the appearance of the so-called Namichimba network of distributary channels in the north-eastern region of the Marsh. The extent of marsh therefore increased relative to the mid-to-late 1880s. This may be attributable to sediment accumulations in the Shire River in this area, deposited by tributaries during the early 1900s. Richards (1954) describes the process in the upper Shire River:
"*As the lake fell* [from 1896 to 1915]*, so the flow down the Shire River decreased year by year and during the wet seasons the tributaries in flood deposited banks of sand and silt in the main channel of the Shire. On these reeds grew and gradually consolidated the banks. Year by year further sand and silt was deposited on these banks until eventually they became so large as to block completely the Shire channel and to stop all flow. This happened early in 1915 and thereafter there was no flow down the Shire except that produced by its tributaries in the wet seasons*."

[375] temperate grasslands, savannas, and shrublands
[376] by backup which enhances sedimentation

"*With its outlet blocked the lake started to rise gradually and in about 1933 began to overtop the silt banks which were blocking its channel. These banks were gradually washed away, the great growth of reeds in the channel was cleared and by about 1937 there was again a broad deep channel from the lake downwards*."

The Marsh is a natural depositional zone, and transported material would have aggraded its channels, with the backup-effect of the railway embankment, and sediment accumulations below the Shire-Ruo confluence enhancing this process. Reduced channel conveyance and higher flows explain the more expansive marsh, illustrated in all the topographical maps from this period. The Shire River experienced the highest flows on record during the late 1970s, and an extensive marsh is evident from remote sensing imagery from this period. The Landsat programme, commencing in the early 1970s, provided an invaluable resource for tracking channel changes since then. During the late 1970s and through the 1980s, distributary channels developed in the upper regions of the Marsh, these being attributed to a combination of high annual flows, reduced sediment loads (the Shire had been flowing strongly for many years) and the effects of floods. During this period, the course along the southern edge of the Marsh was progressively abandoned by the river, and more recently (circa 2000), its western distributary *via* Alumenda was also. There are reports of more-direct human intervention facilitating the latter diversion. Presently, the Shire favours a central course through the Marsh, with the northern Namichimba distributary being characterised by a network of discontinuous channels, which are functionally very important as they filter Shire River sediments.

In addition to this large change in the Shire River's course, to be expected in low-gradient fluvial environments with extensive vegetation, the smaller distributary channels have displayed highly dynamic planforms over the last 75 years or so. Essentially, the planforms of some distributaries have been stable; a few have coalesced to form the Shire River's present day main-stem course; but most have been abandoned with some leaving indications of paleo channels. Historically, hippo populations would have played an important role in channel dynamics (World Bank, 2012):
"*Hippo and crocodile populations have declined severely in recent years and only small groups of the former are now present. Fishermen expressed the view that their population decline has contributed to a gradual 'closing-up' of the vegetation of the marshes, making access more difficult, and leading to the loss of deeper pools which serve as fish nurseries and dry season refuges*."

In the southern region, the channel planforms have been considerably more stable over the past 50 years or so. This is attributed to lower sediment concentrations in the lower Namichimba, and the confining nature of Chiromo Bridge. A somewhat recent change, over the last two decades or so, has been the development of the alternate Shire channel (that flows through the breached embankment), with the progressive abandonment of the Shire's historic course at Chiromo Bridge. Potential continued downcutting of the new channel will further reduce upstream water levels and inundation. These effects are considered transient, however, unless reductions in soil loss from upstream catchments are imminent and substantial.

Although it is difficult to determine the extent of sedimentation, inferences of channel bed aggradation from various[377] data sources are very consistent, suggesting bed sedimentation near Chiromo in the order of 4 m. Results from the longitudinal river bed survey (done for this study) suggest aggradation of at least 2.5 m, further upstream (Figure 6.7). Despite these changes, the shallow lake features prevalent in the southern region have persisted over many decades. This is attributed to their locations, which are associated with either paleo (e.g., Lake Bangula) or existing (e.g., Lake Tomaninjobi) channel courses. The significance of this is that the sediment-filtered flows of

[377] historic photograph, change in gauge plate datum, hydrodynamic modelling and surveyed depth of the alternate Shire channel

the Namichimba channel network pass through Lake Tomaninjobi; Lake Bangula is essentially filled with backup from the Shire River; other smaller lakes are not subjected to direct turbid flows of the Shire River's main-stem channel.

The results from radiocarbon dating of sediment cores extracted from three different locations in the Marsh, support inferences that sediment delivery to the Marsh has increased in recent times. The average rates of sediment accumulation, pre-anthropogenic influence, were in the range of 0.4 to 0.6 mm/yr (for a site located distant to the historical Shire River's course through the Marsh), and 1.3 to 1.7 mm/yr (for a site in closer proximity to the Shire River's course through the Marsh). If recent changes in sedimentation due to human activities are taken to apply to the last 50 years or so, then the data indicates that rates have increased by an order of magnitude or more (*viz*. 10 to 34 mm/yr). In other words, the data, although limited, suggests that floodplain and marsh areas have aggraded by about 0.5 to 1.7 m, over the last 50 years, whereas long-term pre-anthropogenic accumulations were less than 10 cm for the same (50-year) time-span.

Findings from this study show a definitive trend in marsh sedimentation, which is expected given the Marsh's longitudinal position along the Shire River Valley. This is indicated over various time scales, including: the last 1 500 years (radiocarbon sediment dating); and since 1918 (photographic), 1950 (water level monitoring) and 1976 (hydrodynamic modelling). Over shorter time-scales, however, episodes of channel bed incision occur (e.g., 1976 to 1983 and the early 2000s) and these appear to be associated with periods of elevated flow, or increases in annual flow. Although based on limited data sets, estimates of accumulated material in the channels and on the adjacent lands in the Marsh are reasonably consistent**,** being in the order of a few metres over a time span of 50 years or so.

A natural morphological function of the Marsh, and of floodplains during high flows, is sediment retention. In wetland or marsh-type environments, this is greatly enhanced by vegetation, which not only facilitates deposition but also protects the bed material from entrainment (i.e., erosion). Limited data (monthly spot samples) from this study indicates that the Elephant Marsh reduces sediment concentration by an average factor of 2 in the dry season, and by 5 to 20 in the wet season. It is reasonable to expect that changes in the area covered by the Marsh, specifically perennially-inundated indigenous vegetation, will be met with a concomitant change in sediment retention. Unequivocally, the Marsh has responded most effectively to increased sediment loads from upstream and local catchments.

As of November 2014, about half the vegetated area downstream of the Shire-Namichimba split comprised barren or cultivated lands, or burnt areas (e.g., Figure 4.14, bottom). Such a large modification of the indigenous landcover undoubtedly affects hydromorphic processes. An assessment of changes in these and other human pressures within the Marsh are considered in the DRIFT analysis (see Brown *et al.,* 2016).

7.3 Future resilience

Before providing an assessment of the resilience of the Elephant Marsh, it is necessary to define what is meant by 'resilience'.[378] Broadly, it is the ability of a system to cope with change (Wieland and Wallenberg, 2013). The concept of resilience in ecological systems was first introduced by Holling (1973) to describe the persistence of natural ecosystems in the face of changes in ecosystem variables due to natural or anthropogenic causes. Resilience has been further defined as:

- the time required for an ecosystem to return to an equilibrium or steady-state following a perturbation. This definition has been termed 'engineering resilience' (Holling, 1973; Gunderson, 2000);
- the capacity of an ecosystem to absorb disturbance and reorganize while undergoing change so to still retain essentially the same function, structure, identity and feedbacks (Walker *et al.,* 2004). This definition has been termed 'ecological resilience', and it presumes the existence of multiple stable states or regimes (Gunderson, 2000).

Disturbances of sufficient magnitude or duration can profoundly affect ecosystems, resulting in a threshold being reached beyond which a different regime of processes and structures predominates, often of less desirable and degraded conditions (Peterson *et al.,* 1998; Folke *et al.,* 2004). With specific reference to the Elephant Marsh, such disturbances and perturbations would include, natural and anthropogenically-induced climate change, upstream flow regulation and landcover change, local exploitation of natural resources (i.e., in the Marsh), and the introduction of exotic plant species.

Increasingly, aspects of anthropogenically-induced climate change are deemed to be threatening to human communities in many ways, one of which is the increasing frequency of extreme weather conditions. Climate resilience is generally defined as the capacity for a socio-ecological system to maintain function in the face of physical pressures associated with climate change; to adapt, reorganize, and develop more desirable configurations that improve the sustainability of the system, in better preparation for future climate change impacts. With the rising awareness of (anthropogenic) climate change impacts, building climate resilience has become a major objective, with a focus on addressing the vulnerability of communities to its environmental consequences. Communities that rely heavily on a subsistence-based lifestyle, such as those in the villages around the Elephant Marsh, are at high risk. Climate resilience involves an awareness of the situation, risks and vulnerabilities; and an organisational resilience, representing the ability to anticipate, prepare for, and respond in an adaptive way to incremental change and sudden disruptions, to survive and prosper (BS, 2014).

The hydrology of the Marsh is largely determined by flow in the Shire River, the source of which is the outflow from Lake Malawi. The outflow was largely natural pre-1965 and related to lake level, but is now regulated through the Kamuzu Barrage. Notwithstanding large flood events such as those of 1997, 2001 (Figure 2.11) and 2015 (Figure 2.15), discharges have been largely managed at the barrage since the early 1990s, and there is concern over their recent decline since 2015.

Water levels in the lake are a sensitive indicator of regional climate change (Nicholson, 1998), due to the subtle balance between rainfall and evaporation. Lake level fluctuates in response to natural climate change: (refer to Figure 2.17): four dry periods have occurred in the last 900 years, three of these in the last 470 years and two being in the most recent 200 years i.e., their frequency appears to be increasing. While three periods have similar minima (in terms of lake levels), the penultimate occurrence of the 1700/1800s, for which there is "*unquestionable*" evidence (Nicholson, 1998), was substantially lower and of longer duration. This was followed by a relatively wet period during the

[378] material makes use of Wikepedia (https://en.wikipedia.org)

mid-to-late 1800s, when paddle steamers traversed the Marsh, albeit with difficulties during dry seasons. A dry spell spanning a few decades followed during the early 1900s, when the Shire River ceased to flow. A subsequent wet period lasted five decades from about the 1940s, with particularly high flows during the 1970/80s, which is evident in the remote sensing image of Figure 4.13 and the photographic comparisons in Figure 4.14. The relationship between lake level and flow in the upper reaches of the Shire River (pre-1965) means that lake level fluctuations are a good indicator of hydrological change. Delvaux (1995) describes fluctuations (in lake level) during the last 20 000 years or so as "*minor*", compared with changes before that at the temporal scale of lake history.

This serves to illustrate that natural climate change, over recent and much longer time frames, has resulted in large hydrological perturbations in the Elephant Marsh. The previous section (7.2) provided descriptions of the Marsh over the last 157 years, which included periods of alternating wet, dry, and wet conditions. Furthermore, there seems to be unequivocal evidence for a preceding dry period (in the 1700/1800s), and more recently, since the 1980s, of a general trending decrease in flows. Two apparently contradictory assessments of the resilience of the Marsh emerge:

- that it demonstrates a high resilience to natural climate change, given its return to a similar state following dry periods; this assumes the existence of various states within a dynamic regime that defines the 'Marsh': i.e., predominantly semi-permanent marsh and shallow lakes during wet periods, and largely savannah grassland with seasonal wetlands and scattered pools during dry periods;
- a low resilience due to its inability to absorb climatic perturbations and to retain essentially the structure and function that exists 'today'.

The apparent contradiction stems from different temporal scales, which have not been explicitly defined for this study. Within the context of the broader climate-resilient livelihoods project, the second assessment is deemed to apply. This is because the reference condition is the present state of the Marsh, and changes to this over short time-frames affect largely subsistence-based lifestyles. Given the dynamic behavior of the Marsh in response to hydrological regimes that are sensitive to climate change, it is necessary to define what is meant by the structure and function of the Marsh, as it exists 'today'. The hydrodynamic modelling, described in Chapter 5, develops a physical template[379] that refers to conditions in recent years (2013 to 2015), based on data availability, and this is taken to represent existing (and baseline) conditions.

Shire River flows are the primary determinant of marsh inundation, and as has been shown, are sensitive to natural climate change through fluctuating water levels in Lake Malawi. During the last two centuries, historical accounts indicate that the Marsh's structure has changed considerably during wet and dry periods. It therefore follows that over relatively short time frames (i.e., less than a century), the Marsh will display a low resilience to natural climate change, through its inability to retain a similar state and function to what exists today. A sub-study of the broader Elephant Marsh's Project is the DRIFT assessment (refer to Brown *et al.,* 2016), which provides an analysis of the potential effects of alternative future scenarios of flow and/or management options on the (baseline) ecological condition of the Marsh. Effectively, this provides a measure of its future ecological resilience over the shorter-term.

In terms of the Marsh's morphological resilience, the main anthropogenic disturbances are increased sediment loads; physical structures - specifically the Chiromo Bridge and its flanking embankment;

[379] which includes landcover

land degradation within the Marsh; and global climate change. With the possible exception of global climate change,[380] impacts of these disturbances are reflected in the existing morphology.

Most likely, the largest changes in the Marsh's morphology are due to sedimentation, as well as changes in landcover arising from cultivation in the floodplain and marsh (e.g., Figure 4.14). Landcover changes in the Marsh have been extensive since the 1980s, particularly in the upper and western regions where declining flows (and inundation) have presented opportunities for the ingress of people, together with their subsistence activities. It is difficult to quantify the effect of this on the morphology. Suffice it to say that loss of indigenous landcover typically results in reduced sediment retention, particularly when that loss results in bare lands or burnt areas - the latter being prevalent in the Marsh. In the western region of the Marsh, where the Shire River used to flow, ~80% of the present day indigenous landcover has been degraded; this comprising ~64% of the total marsh area when fully inundated. To some extent, this offsets sediment retention of the Marsh, which although based on a limited data set, nonetheless appears to be advancing at a very high rate compared with pre-anthropogenic long-term averages. The combined effects of increased sediment delivery to the Marsh, reduced sediment retention of the upper/western region, and backup effects from downstream are likely to have resulted in considerable increases in sediment retention in the eastern/central/southern regions of the Marsh. This area comprises the bulk of intact marsh habitat, and is therefore at greatest risk of loss.

The dynamic network of narrow and shallow distributary channels flow through the eastern and central regions of the Marsh, indicate high rates of sediment delivery and retention. Arguably, the process of channelisation, whereby channels become progressively deeper and wider resulting in lower connectivity with the adjacent area (marsh or floodplain), is the largest risk to loss of marsh habitat. Findings from this study indicate that both the channels and adjacent floodplain/marsh are experiencing sedimentation. This, combined with the somewhat pragmatic view that sediment delivery to the Marsh is unlikely to be substantially reduced in the (near) future, leads to an assessment of a low risk of channelisation. Of greater risk (in respect of loss of marsh habitat) are declining Shire River flows (i.e., the underlying sensitivity to natural climate change), to which the Marsh has low (short-term) resilience. The numerous shallow lakes are particularly threatened by reduction in flows, for reasons discussed previously. As articulated in Chapter 6, future loss of the most extensive lake, Tomaninjobi, and other south-eastern lakes, by infilling of Ruo River sediments, seems inevitable. Returning the Ruo River to its pre-2015 course will avert this short-term lake-siltation, but given the underlying issue of sedimentation in the Ruo, confining it to its historic course will be a challenge.

Finally, the issue of anthropogenic climate change, ostensibly the 'climate change' the project refers to. Human-induced climate change projections are described in detail in Section 3.5. Although there is some uncertainty surrounding some of the effects, all studies concur about an increase in the intensity of extreme rainfall events. This, combined with higher erosivity, and the current trajectory of channel and marsh sedimentation, means that the frequency and extent of marsh inundation, during floods, is likely to increase. High flows are generally associated with high sediment loads that smother cultivated lands - a natural process of floodplain aggradation, but exacerbated in the Shire Valley by recent human activities in the upstream catchment. The projected future is a reduction in diversity of hydraulic habitat, particularly shallow lakes and open water areas, as siltation reduces the depths of these features, which can lead to an ingress of marsh vegetation such as reeds and papyrus. The perceived resilience to these morphological changes is low. Increased sedimentation of topographical depressions in the marsh landscape, when associated with reduced Shire River flows

[380] There are conflicting views as to whether the effects of anthropogenically-induced climate change have already manifested themselves - refer to Section 3.5.

(natural or regulated), provides new opportunities for turning marshland into cultivated lands. The consequences of people farming what are essentially fluvial environments (i.e., the deposits and landforms created by river processes) is all too apparent during floods:

"*I flew over some parts of the Lower Shire but we could not find anywhere to land. It's a big challenge we have before us. Thousands of homes had been destroyed, hundreds of hectares of crops submerged and livestock had been washed away*."[381]

Malawian vice-president, Saulos Chilima, January 2015

This concludes the reporting on the hydromorphology of the Marsh. The discussions and findings presented here, as well as results of the hydrodynamic modelling, were used directly (e.g., as in DRIFT) and to inform other aspects and sub-studies of the Elephant Marsh's 'Climate resilient livelihoods and sustainable natural resources management' Project.

[381] https://www.theguardian.com/world/2015/jan/17/malawi-floods-kill-176-people

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9 Appendix

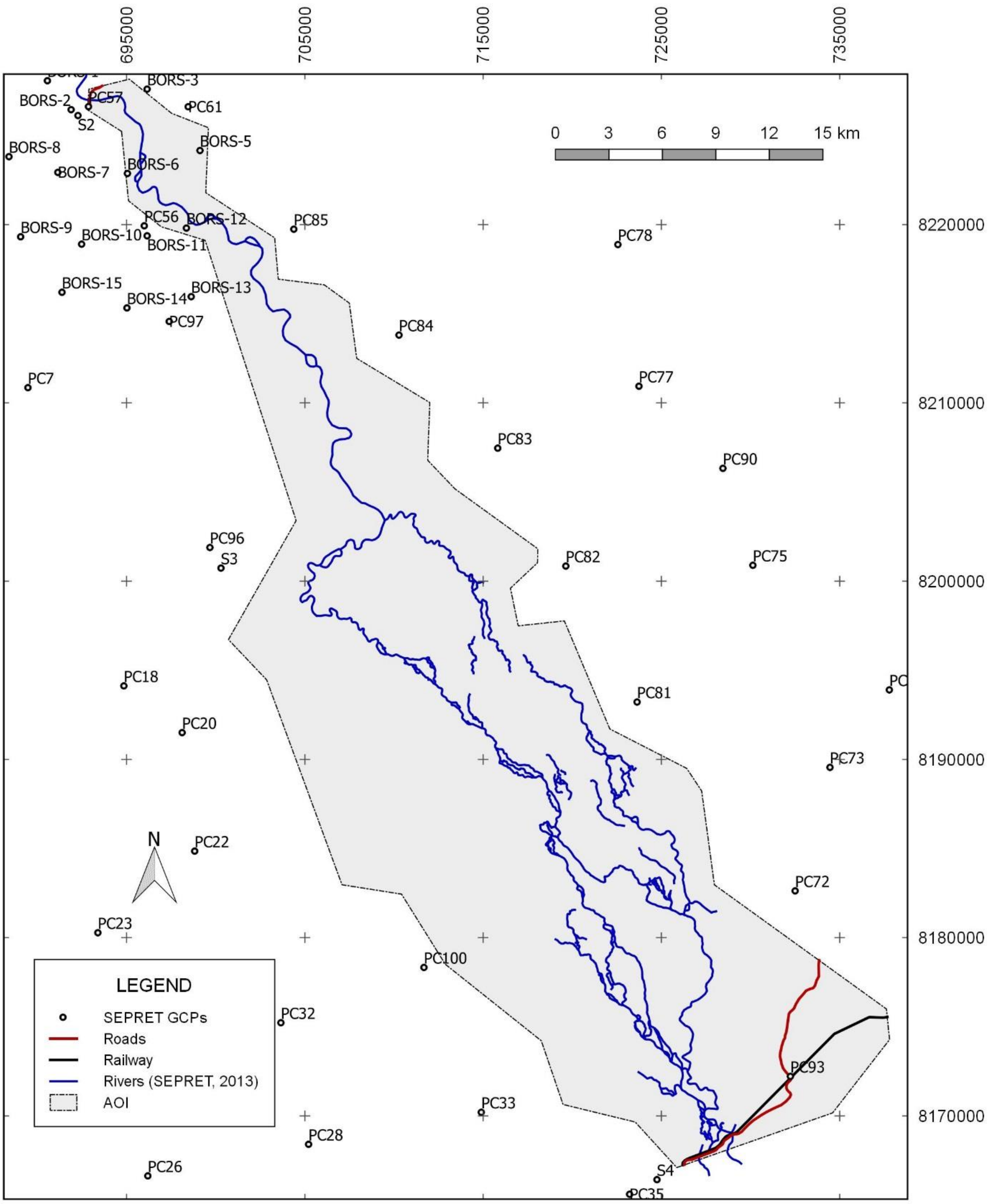

Figure A1 Position of Ground Control Points (GCPs) used in the SEPRET 2013 survey

Table A1 Water chemistry variables measured at the four suspended sediment sampling sites (S1-4) in Figure 4.19

Sample (S)	Date	pH	EC	Na	K	Ca	Mg	Fe	Cl	CO_3^{2-}	HCO_3^-	SO_4	B	Mn	Cu	Zn	P	NH_4-N	NO_3-N	F	TDS	T	Sediment concentration
		@25°C	mS/m	mg/l																		°C	mg/l
1	Jul 2015	7.8	24.9	19.8	6.7	12.5	8.1	0.08	6.0	0.0	129.0	2	0.03	0.01	0.00	0.00	0.00	0.26	0.21	0.5	159	1.7	38
	Aug 2015	8.2	25.1	23.7	6.0	13.1	8.0	0.05	6.0	0.0	140.0	4	0.02	0.00	0.01	0.01	0.02	0.19	0.03	0.1	161	18.0	96
	Sep 2015	8.1	29.3	26.2	7.9	17.8	10.4	0.12	10.4	24.2	105.4	6	0.10	0.00	0.01	0.01	0.08	0.28	0.01	0.6	188	23.3	20
	Nov 2015	7.7	30.1	23.3	7.0	18.7	8.7	0.09	10.5	10.9	175.6	5	0.13	0.00	0.00	0.00	0.08	0.19	0.02	0.3	180	24.5	38
	Dec 2015	8.1	28.3	22.6	7.8	20.6	8.3	0.13	8.0	0.0	164.0	49	0.20	0.00	0.01	0.04	0.03	0.35	0.03	0.4	181	26.7	32
	Jan 2016	7.8	25.6	21.1	6.5	15.9	7.3	0.05	7.0	0.0	156.0	4	0.10	0.00	0.00	0.00	0.07	0.18	0.00	0.4	164	13.1	112
	Feb 2016	7.5	26.1	17.5	5.7	18.8	7.5	0.18	11.8	0.0	137.1	3	0.30	0.00	0.00	0.00	0.05	0.16	0.00	0.3	157	24.1	155
	Mar 2016	7.4	19.1	11.0	4.0	16.3	5.1	0.48	9.0	0.0	106.7	0	0.04	0.00	0.00	0.02	0.14	0.21	0.01	0.4	115	20.4	831
	Apr 2016	8.8	21.3	190.0	8.5	9.6	8.8	0.32	8.0	7.0	0.0	24	1.57	0.01	0.01	0.00	0.03	0.31	0.00	0.6	137	12.1	136
	May 2016	8.0	23.7	21.2	6.4	15.0	7.9	0.21	7.0	0.0	141.0	3	0.07	0.00	0.01	0.00	0.02	0.12	0.04	0.6	179	10.5	27
	Jun 2016	7.9	27.9	23.5	6.0	19.8	9.3	0.18	9.0	12.1	143.6	5	0.06	0.00	0.01	0.00	0.02	0.10	0.05	0.8	172	17.2	65
	Jul 2016	7.8	28.8	21.1	6.4	20.4	7.7	0.20	8.0	0.0	214.0	3	0.08	0.03	0.02	0.03	0.01	0.28	0.36	0.8	185	15.6	33
2	Jul 2015	8.0	26.1	19.1	6.4	18.6	7.9	0.16	15.8	13.5	151.5	2	0.03	0.01	0.03	0.01	0.04	0.32	0.13	0.6	158	7.4	11
	Aug 2015	8.0	28.6	24.4	6.2	18.0	9.0	0.03	11.0	0.0	160.0	3	0.02	0.00	0.01	0.00	0.01	0.20	0.02	0.0	183	18.2	36
	Sep 2015	7.8	34.4	25.5	6.8	24.5	10.8	0.11	10.1	12.1	155.9	5	0.07	0.00	0.01	0.01	0.09	0.24	0.00	1.0	220	22.4	12
	Nov 2015	7.4	35.4	24.2	6.9	27.2	9.5	0.06	12.3	0.0	225.5	4	0.09	0.01	0.01	0.01	0.08	0.18	0.01	0.3	212	25.0	30
	Dec 2015	8.2	33.1	24.5	9.2	22.7	9.3	0.28	10.0	0.0	183.0	25	0.17	0.00	0.00	0.01	0.03	0.27	0.03	0.4	212	26.8	218
	Jan 2016	7.6	30.9	22.0	6.3	23.9	8.4	0.05	8.0	0.0	193.0	4	0.10	0.00	0.00	0.00	0.04	0.17	0.00	0.4	198	13.6	157
	Feb 2016	7.4	36.9	19.8	7.1	33.7	8.8	0.66	11.0	0.0	218.9	2	0.26	0.00	0.01	0.00	0.09	0.19	0.00	0.2	221	24.2	33
	Mar 2016	7.5	29.1	17.4	5.7	27.9	8.1	0.33	11.8	0.0	209.6	1	0.04	0.00	0.01	0.02	0.09	0.24	0.00	0.5	174	19.8	36
	Apr 2016	8.4	21.9	40.3	6.1	12.7	7.6	0.23	10.0	2.0	0.0	7	0.34	0.01	0.01	0.00	0.00	0.19	0.02	0.5	140	12.5	462
	May 2016	7.8	28.0	22.8	6.5	20.5	9.1	0.22	9.0	0.0	169.0	3	0.05	0.00	0.01	0.00	0.00	0.11	0.01	0.6	179	11.0	49
	Jun 2016	7.7	30.1	25.5	6.5	22.6	10.2	0.21	7.0	0.0	213.0	3	0.06	0.00	0.01	0.00	0.02	0.10	0.00	0.6	193	17.3	45
	Jul 2016	7.1	31.7	21.4	6.1	23.8	8.0	0.30	8.0	0.0	244.0	3	0.08	0.03	0.02	0.03	0.01	0.28	0.36	0.7	203	15.9	19

Table A1 (cont.) **Water chemistry variables measured at the four suspended sediment sampling sites (S1-4) in Figure 4.19**

Sample (S)	Date	pH	EC	Na	K	Ca	Mg	Fe	Cl	CO_3^{2-}	HCO_3^-	SO_4	B	Mn	Cu	Zn	P	NH_4-N	NO_3-N	F	TDS	T	Sediment concentration
		@25°C	mS/m	mg/l																		°C	mg/l
3	Jul 2015	8.1	18.4	9.1	2.8	14.5	6.9	0.11	8.0	0.0	88.0	3	0.02	0.01	0.01	0.00	0.03	0.25	0.18	0.3	117	1.9	24
	Aug 2015	8.3	18.3	10.8	1.6	13.1	8.0	0.03	7.0	1.0	160.0	3	0.01	0.00	0.01	0.01	0.00	0.19	0.02	0.0	117	19.0	31
	Sep 2015	7.9	25.6	13.9	3.0	20.4	10.3	0.11	11.2	12.1	117.1	6	0.05	0.00	0.01	0.01	0.11	0.24	0.01	0.4	164	22.3	10
	Nov 2015	7.6	29.4	14.2	2.5	25.2	10.5	0.43	11.9	0.0	150.9	6	0.08	0.00	0.00	0.00	0.12	0.22	0.05	0.3	176	25.0	45
	Dec 2015	8.0	17.6	4.1	2.1	26.3	2.6	0.61	5.0	0.0	100.0	18	0.14	0.01	0.00	0.00	0.02	0.27	0.03	0.2	113	27.1	179
	Jan 2016	7.9	9.9	4.7	1.8	10.1	2.2	0.13	4.0	0.0	60.0	3	0.09	0.00	0.00	0.00	0.07	0.17	0.00	0.3	63	14.6	359
	Feb 2016	7.7	17.2	6.4	2.0	20.0	2.8	0.39	12.5	0.0	83.8	2	0.28	0.00	0.00	0.00	0.03	0.22	0.00	0.2	103	24.0	92
	Mar 2016	7.0	6.8	4.5	2.1	4.9	2.3	1.94	10.4	0.0	38.5	0	0.03	0.01	0.01	0.02	0.14	0.26	0.59	0.3	41	20.3	1129
	Apr 2016	8.0	14.0	16.3	1.4	20.6	2.5	0.25	7.0	0.0	83.0	4	0.17	0.00	0.01	0.00	0.00	0.19	0.01	0.2	89	13.1	130
	May 2016	8.4	9.6	5.0	1.0	11.7	2.8	0.23	6.0	2.0	169.0	2	0.03	0.00	0.01	0.00	0.00	0.12	0.01	0.3	62	11.0	142
	June 2016	7.7	11.3	6.3	1.2	9.4	4.2	0.20	6.0	0.0	78.0	2	0.05	0.00	0.00	0.00	0.02	0.10	0.00	0.3	73	18.0	35
	Jul 2016	7.1	11.2	4.7	0.9	11.0	3.3	0.20	5.0	0.0	73.0	2	0.08	0.03	0.02	0.03	0.02	0.28	0.36	0.3	72	16.0	12
4	Jul 2015	7.7	28.9	18.7	5.6	19.8	8.3	0.16	8.0	0.0	153.0	2	0.03	0.01	0.00	0.00	0.02	0.26	0.11	0.5	185	3.4	78
	Aug 2015	8.0	28.8	23.5	5.2	19.0	9.1	0.03	7.0	0.0	163.0	2	0.02	0.00	0.01	0.01	0.00	0.19	0.03	0.1	184	18.2	27
	Sep 2015	8.0	31.9	24.8	7.9	18.6	10.0	0.11	9.7	15.8	119.5	5	0.05	0.00	0.01	0.01	0.09	0.23	0.01	0.5	204	23.0	12
	Nov 2015	7.4	34.7	24.7	6.5	27.2	9.4	0.05	10.5	0.0	195.9	4	0.08	0.00	0.01	0.00	0.08	0.15	0.01	0.3	208	25.0	18
	Dec 2015	8.2	30.2	23.2	8.4	21.6	8.8	0.45	9.0	0.0	170.0	14	0.13	0.01	0.00	0.00	0.04	0.26	0.08	0.3	193	27.1	244
	Jan 2016	7.6	34.4	22.2	6.6	31.2	7.8	0.05	10.0	0.0	236.0	4	0.10	0.00	0.00	0.00	0.05	0.17	0.01	0.3	220	14.9	149
	Feb 2016	7.4	41.4	20.4	6.2	42.3	7.8	0.19	12.3	0.0	239.1	3	0.25	0.09	0.00	0.00	0.05	0.17	0.00	0.2	248	24.0	40
	Mar 2016	7.5	32.0	18.1	5.9	31.1	7.8	0.32	11.5	0.0	190.0	1	0.03	0.00	0.00	0.02	0.08	0.17	0.00	0.5	192	20.3	132
	Apr 2016	8.0	26.4	26.3	6.6	18.1	8.1	0.23	11.0	0.0	161.0	4	0.10	0.02	0.01	0.00	0.00	0.14	0.01	0.4	169	13.7	591
	May 2016	7.8	31.0	22.4	6.6	26.1	8.8	0.22	9.0	0.0	202.0	3	0.04	0.00	0.01	0.00	0.00	0.10	0.01	0.6	198	11.1	106
	Jul 2016	7.7	27.9	23.5	6.0	19.8	9.3	0.18	9.0	0.0	195.0	3	0.06	0.00	0.00	0.00	0.01	0.10	0.00	0.6	178	18.0	35
	Jul 2016	7.0	31.7	23.2	6.7	26.8	8.6	0.20	8.0	0.0	216.0	3	0.06	0.03	0.02	0.03	0.02	0.28	0.36	0.7	203	16.1	28