STREAMFLOW SIMULATION AND ENVIRONMENTAL FLOW ASSESSMENT IN THE UMBA RIVER, KENYA

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Streamflow Simulation and Environmental Flow Assessment in the Umba River, Kenya

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DECLARATION

This Thesis is my original work and has not been presented for a degree in this or any other University.

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DEDICATION

I would like to dedicate this Thesis to my Parents for their unlimited supports during my studies.

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ABBREVIATIONS AND NOTATIONS

AEZs	Agro-Ecological Zones
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information Systems
ASAL	Arid and Semi-Arid Land
ASCE	American Society of Civil Engineers
BBM	Building Block Methodology
CBD	Convention on Biological Diversity
CDA	Coast Development Authority
CE	Civil Engineering
CPD	Computer Program Documentation
CRC	Coastal Resources Center
CWSB	Coast Water Services Board
DEM	Digital Elevation Model
DSS	Data Storage System
DSSVue	Data Storage System Visual Utility Engine
DTM	Digital Terrain Model
EFA	Environmental Flow Assessment
EFM	Ecosystem Functions Model
EFR	Environmental Flow Requirement
ELOHA	Ecological Limits Of Hydrologic Alteration
ESA-DUE	European Space Agency - Data User Element
ET	Evapotranspiration
FDC	Flow Duration Curve
FIU	Florida International University
FP	Flow Profile
GeoHMS	Geospatial Hydrologic Modelling System
GeoRAS	Geospatial River Analysis System

GIS	Geographic Information Systems
GLOWS	Global Water for Sustainability Program
GPS	Global Positioning System
GQ	Geographical Queries
GUI	Graphical User Interface
GWP	Global Water Partnership
H	Stage or Water Level
HEC	Hydrologic Engineering Center
HMS	Hydrologic Modelling System
ICZM	Integrated Coastal Zone Management
IHA	Indicators of Hydrological Alteration
ISRIC	International Soil Reference and Information Centre
IUCN	International Union for Conservation of Nature and Natural Resources
IWRM	Integrated Water Resources Management
JKUAT	Jomo Kenyatta University of Agriculture and Technology
KE	Kenya
KFS	Kenya Forestry Service
KMFRI	Kenya Marine and Fisheries Research Institute
MEA	Millennium Ecosystem Assessment
MEWNR	Ministry of Environment, Water and Natural Resources
MoALF	Ministry of Agriculture, Livestock and Fisheries
MoU	Memorandum of Understanding
NASA	National Aeronautics and Space Administration
P	Precipitation
PAUSTI	Pan African University Institute for basic Sciences, Technology and Innovation
PBWO	Pangani Basin Water Office
PFMP	Participatory Forest Management Plan

POWER	Prediction of Worldwide Energy Resource
Q	Discharge
R^2	Coefficient of Determination
RAS	River Analysis System
RC	Rating Curve
RS	River Station
RVA	Range of Variability Approach
S	Slope
SCS	Soil Conservation Survey
SOTER	Soil and Terrain
SPI	Standardized Precipitation Index
SQ	Statistical Queries
STEs	Shared Trans-Boundary Ecosystems
TZ	Tanzania
UNESCO	United Nations Educational, Scientific and Cultural Organisation
URB	Umba River Basin
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
V	Velocity
VAJIKI	Vanga, Jimbo and Kiwegu
WGS	World Geodetic System
WMO	World Meteorological Organization
WMS	Watershed Modeling System
WRA	Water Resources Authority
WS	Water Surface
σ	Standard Deviation

ABSTRACT

The Umba River basin is a transboundary river catchment shared between Kenya and Tanzania. There are plans to construct two dams in the catchment to meet the water demands for irrigation and water supply. Hence, there is growing concern on the alteration of the river flow that can significantly affect the functioning of the riverine ecosystems. The integration of hydrologic, hydraulic, and ecological data is necessary to understand the flow characteristics and to assess the environmental flows of the river. However, sufficient streamflow observations are not available due to missing flow records and limited observation periods in the river. The overall objective of the study was, therefore, to conduct an environmental flow assessment for the lower reach of the river using observed and simulated streamflow data. A rainfall-runoff model is simulated using Hydrologic Modelling System (HMS) to determine continuous time series of daily streamflow for the last 30 years. The statistical relationships between the historical flow regime and the Umba River ecosystems are evaluated by the use of Ecosystem Functions Model (EFM). A hydraulic model was setup using River Analysis System (RAS) to simulate the streamflow in the lower 45 km Umba River reach. Results from the hydraulic model were used to investigate the relationships between the flow characteristics and the natural environmental flows of the river. Different flow requirements including low flows (0.20 m^3/s to 0.70 m^3/s), base flows (0.7 m^3/s to 4.0 m^3/s), pulses (4 m^3/s to 20 m^3/s), high flows (20 m^3/s to 50 m^3/s), and flood events (50 m^3/s to 120 m^3/s) are identified. These flow types need to flow in different months of the year to preserve the riverine ecosystems and maintain their services. For effective management of the river flow, consideration of environmental flows and continuous collection of data on hydrology, hydraulics, and ecology are recommended.

CHAPTER ONE

INTRODUCTION

1.1. Background to the Study

Water has been managed for the primary uses of domestic supply, irrigated agriculture, industrial uses, hydropower generation, and navigation with an emphasis on economic growth. To achieve these needs; water impoundments, run-of-river abstractions, diversions, interbasin water transfers, and exploitation of aquifers have been developed. All these developments have helped to attain steady and dependable water supplies and to moderate extreme water conditions such as floods and droughts (Richter, Matthews, Harrison, & Wigington, 2003; Tharme, 2003; Wakitolie, 2013).

The hydrological alterations by water resource developments, however, have changed ecosystem structures and processes in running waters and their associated environments. The manipulation of the flow regimes of rivers to provide water for various purposes have resulted in a growing deterioration of riverine ecosystems (Bunn & Arthington, 2002; King, Tharme, & Villiers, 2008). In addition to modifying the environment at the development sites, riparian communities upstream and downstream have been affected by flow regime alterations and water level fluctuations (Nilsson & Berggren, 2000). Riparian zones have been fragmented and greatly reduced in width and streams have been filled with sediments and high levels of nutrients (Lake, 2005).

Various factors reflect the nature of the river’s flow pattern and determine the health of riverine ecosystems. Some of these include water flows, channel type, water quality, the biotas of the river, and the management of the flow regime (Acreman &

Dunbar, 2004). Water flow and the shape of the channel are the primary determinants of physical habitat in rivers, which in turn influence the ecosystem functions of flora and fauna (CRC, 2008).

Flow regimes play major roles in regulating the biotic structures, compositions, and functions of aquatic, riparian, and wetland ecosystems (Richter, Baumgartner, Powell, & Braun, 1996; Richter et al., 2003; Wakitolie, 2013). The hydrologic components of a natural flow regime control many of the physical, chemical, and biological processes that sustain biological diversity and ecosystem services of rivers (Bunn & Arthington, 2002; Carlisle, Falcone, Wolock, Meador, & Norris, 2010). On the other hand, alterations of a river from its natural conditions modifies habitat attributes and impairs ecosystems (Speed, Yuanyuan, Quesne, Pegram, & Zhiwei, 2013; Wang, Wang, & Wu, 2015).

The alteration of flow regimes affects the biodiversity and ecosystem functions of rivers and their associated floodplains (Bunn & Arthington, 2002; Nilsson & Berggren, 2000). Flow alteration involves modification of the natural flow regime components in magnitude, duration, timing, frequency, and rate of change (Poff & Zimmerman, 2010). In rivers where the flow pattern has been altered by man, all of these components are likely to change from their natural conditions (King et al., 2008). To provide sufficient freshwater flows and maintain the essential goods and services provided by rivers, therefore, the components of the natural flow regime need to be investigated (Arthington, Bunn, Poff, & Naiman, 2006). This requires performing streamflow simulations to understand the key components of the flow regime and their roles in maintaining the health of the ecosystems.

A range of methods have been developed to simulate streamflows (Devia, Ganasri, & Dwarakish, 2015) and a wide range of research works have been undertaken on environmental flow assessments (Hickey, Huff, & Dunn, 2015). However, managing streamflows and ecosystem functions has become the subject of considerable research and debate (Doyle, Stanley, Strayer, Jacobson, & Schmidt, 2005; Julian et al., 2015; Poff et al., 2010; Richter, 2010). Early recognition that certain minimum flows were required to maintain river biota (Bunn & Arthington, 2002; Tharme, 2003) have evolved to a more comprehensive view of environmental flows (Carlisle, Falcone, et al., 2010). Therefore, detailed understanding of how flow affects ecological conditions remains an open scientific challenge (Murphy, Knight, Wolfe, & Gain, 2012; Poff et al., 2010; Poff & Zimmerman, 2010).

1.2. Statement of the Problem

The Umba River basin is a transboundary river catchment shared between Kenya and Tanzania. The area is endowed with unique and endemic plant and animal species in the coastal area. Freshwater input from the river is a major factor controlling the estuarine production which is critical for the biodiversity of the coastal and marine ecosystems, and the livelihoods they support. Due to the threats from the growing human pressures and climate change-related effects, however, there is growing concern on the alteration of the river flow that can significantly affect the functioning of the estuary (Mitto et al., 2013).

The lower catchment has a great potential for large-scale irrigation and there are plans to construct two dams on the catchment to meet the water demands for irrigation and water supply (Lerise, 2005). After development of the dams, the amount of water withdrawn from the river is likely to increase, leading to a decrease in the amount of freshwater delivered to the estuary. The flow characteristics in the river will also be altered by the reservoir. This will cause negative impacts on the ecosystems in the lower reach of the river. Therefore, environmental flow assessments need to be done to preserve the riverine and estuarine ecosystems and sustain their services.

Long time series of streamflow data and their flow pattern are required to understand the flow characteristics and to assess environmental flows of rivers. Reliable estimate of river flows generated from catchments are commonly obtained by water level observations from in situ gauging stations. However, sufficient observations are not available in the Umba River due to missing records and limited observation periods. These gaps and discontinuities present problems in planning water development projects and managing water resources to meet developmental and environmental needs. In view of the planned future developments in the Umba River, this study aims to create a discharge time series which can be used for planning and to perform environmental flow assessments which can serve as a baseline to assess impacts of future water resources development in the basin.

1.3. Objectives

1.3.1. General objective

The overall objective was to conduct an environmental flow assessment for the lower reach of the transboundary Umba River using observed and simulated streamflow data.

1.3.2. Specific objectives

The specific objectives of this study were:

1. to determine continuous time series of daily naturalized streamflow for the last 30 years in the Umba River using HEC-HMS model;
2. to evaluate the statistical relationships between the historical natural flow regime and different ecosystem groups of the Umba River using HEC-EFM model; and
3. to establish the relationships between the hydraulic flow characteristics and the natural environmental flows for the lower reach of the Umba River using HEC-RAS model.

1.4. Research Questions

This research has answered the following questions.

1. *What daily streamflows have been experienced in the Umba River Basin in the last 30 years?*
2. *What are the statistical relationships between the flow regime and the different ecosystem groups of the Umba River under the flow conditions of the last 30 years?*
3. *What are the relationships between the hydraulic flow characteristics and the natural environmental flows in the lower reach of the Umba River?*

1.5. Significance of the Study

Watershed management coupled with eco-region conservation is rapidly emerging as an essential strategy of natural resources management that provides human development opportunities and sustains biological diversity (Abell, Thieme, Dinerstein, & Olson, 2002; Rathod, Borse, & Manekar, 2015). The maintenance of natural biodiversity is the key to the health of ecosystems and to their sustainable utilisation. The conservation and sustainable use of biodiversity is essential for the survival of humans and protecting the environment. Fresh water maintains riverine and estuarine biodiversity which simultaneously serve multiple aspects of human well-being and provide a wealth of goods and services for societies (Forslund et al., 2009). To sustain these benefits and maintain freshwater biodiversity, the freshwater flows must be better managed (Richter et al., 2003).

Understanding the relations among watershed, water flow, and ecological health is important (Knight, Gain, & Wolfe, 2011). Hydrologic and hydraulic modellings are required for basin planning and management, ranging from flood regulation to assessment of environmental flows. Hydrologic models allow us to study the functioning of watersheds and their response to various inputs, and thereby gain a better understanding of hydrologic processes (Tiwari, Gaur, Sonal, & Nakum, 2013). Accurate surface runoff estimation plays a significant role for the efficient management of watersheds and ecosystems (Tiwari et al., 2013). Hydraulic modelling enables simulation of the river flow which is essential for the investigation of the hydraulic flow characteristics.

Environmental flow assessment (EFA) describes the water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems. The objectives of EFA can be directed for the enhancement of riverine ecosystems, for conserving endangered species, or for maintaining ecosystem services (Tharme, 2003). The assessment can be done for mitigation purposes, to advice on releases that would reduce the impacts of in-river developments or for the purposes of restoration to advice on flows that would partially reverse past degradations. Thus, EFA assists in decision making on the management of existing and future water resource developments (King et al., 2008).

Provision of sufficient freshwater flow ensures the functioning of riverine ecosystems and maintains the goods and services sustained by the water-dependent ecological processes (Rivaes, Boavida, Santos, Pinheiro, & Ferreira, 2017). Natural flow variability is the primary determinant of riverine ecosystem structure and function. Maintaining natural hydrologic variability determines the structure and function of riverine ecosystem which is essential for conserving native riverine biota and integrating the river ecosystems (King et al., 2008; Wakitolie, 2013). On the other hand, alterations from the natural hydrologic regimes modify habitat attributes and impair ecosystem connectivity (Speed et al., 2013; Wang et al., 2015). The river environment and the functional integrity of the riverine ecosystem can be maintained if the features of the natural flow regime can be identified and adequately incorporated into a modified flow regime (King et al., 2008; Wakitolie, 2013).

The Umba River estuary requires adequate freshwater flows to preserve the estuarine ecosystems and maintain their services. Implementation of effective EFA in the river ensures balancing the water use and mitigating environmental degradation. This is essential for conservation of the biodiversity that supports human life, livelihoods, and health of the ecosystems. The study is expected to help management decisions for efficient water resource allocation, enhancing Integrated Water Resources Management (IWRM), and maximizing ecological benefits in the river. Moreover, the study provides baseline information for cross-border collaboration for integrated management of Shared Trans-Boundary Ecosystems (STEs) in the basin. This would eventually ensure sustainable supply of goods and services for enhanced socio-economic development and ecosystem functioning.

1.6. Justification

With increased population growth and socio-economic development, the demand for water is increasing in the Umba River Basin. A sustainable approach to water management is sought to be achieved through an integrated water resources management which requires environmental flow assessment studies. Such an approach is necessary for maintaining the ecosystems that are providing the basic services supporting the lives and livelihoods of the local communities (Kwale, 2013; MoALF, 2016; VAJIKI PFMP, 2017).

The natural flow variability of rivers creates and maintains hydrological and ecological connectivity between the channel, floodplain, wetland and estuary. The ecosystem functions and biodiversity have evolved under this natural river flow variations. Rivers with highly altered flows lose their ability to support the natural processes of maintaining healthy and diverse ecosystems. This in turn diminishes the services provided by the ecosystems. It is therefore essential to understand the linkages between seasonal freshwater inflow and the riverine ecosystems (FIU-GLOWS, 2016).

The integration of hydrologic, hydraulic, and ecological data is essential to develop the assessment of environmental flows in the Umba River. The historical natural flows entering the estuary need to be investigated to extract ecologically meaningful flow components that capture the natural flow variability. As the river’s channel is strongly influenced by flow, the geomorphologic field data should also be collected and assessed to describe the nature of water flows. Assessment of the environmental flows in the river, therefore, requires understanding the key components of the flow regime and their roles in maintaining the health of the ecosystems (Arthington et al., 2006; Poff et al., 2010; Poff & Zimmerman, 2010).

River management requires scientific approaches to understand the relationships between streamflows and biological integrity (Carlisle, Wolock, & Meador, 2010). Hydrological modelling that estimates long term and continuous time series of daily streamflow can be applied for studies of water availability, flow regulation, and other water management plans. Analysis of the relationships between the historical flow regime and the ecosystems of the river helps to identify important flow dynamics that satisfy the timing of species life stages and requisite conditions for their success. Hydraulic modelling can be used to establish the relationships between the flow characteristics and the natural environmental flows. Hence, the study will assist in the decision process regarding the release of water below the dams and in the management of the transboundary basin where communities living in the upstream areas could manage the watershed in a way that maintains the ecosystems. This will promote management decisions that are opportunistic, water-efficient, and maximize ecological benefits in the area.

1.7. Scope of the Study

This research covers the assessment of environmental flows in the lower reach of the transboundary Umba River using observed and simulated streamflow data. To achieve this objective, the study involved combined approaches of literature review, data collection and analysis, fieldwork, and modelling. A rainfall-runoff model is developed using HEC-HMS to determine continuous time series of daily streamflow for the last 30 years. HEC-EFM model is used to evaluate the statistical relationships between the historical natural flow regime and different ecosystem groups of the river. The relationships between the hydraulic flow characteristics and the natural environmental flows of the lower river reach are established using HEC-RAS model. The research does not cover studies on water quality and sediment analysis due to shortage of time and financial limitations.

CHAPTER TWO

LITERATURE REVIEW

2.1. Riverine Ecosystems

An ecosystem consists of abiotic (soil, water, air) and biotic parts (flora, fauna) that work together. It is a dynamic complex of the living communities and the nonliving environment, interacting as a functional unit (Millennium Ecosystem Assessment, 2003). Each ecosystem is the result of many years of interaction between physical, chemical and biological components of many ecosystems (Dickens, 2011). Ecosystems are broadly classified as natural ecosystems and man-made ecosystems. One class of the natural ecosystems is the riverine ecosystem comprising aquatic, riparian, wetland, and estuarine ecosystems which are mainly affected by flow regime alterations. Flooding plays an important role in the ecology of riparian and floodplain plant communities and water drains off the land occupied by these communities soon after the recession of floodwaters. Wetlands are considered as water storage systems while riparian zones and floodplains act as conduits for the water transmission (Wakitolie, 2013).

In any ecosystem, physical processes create the habitats that support biodiversity. In lotic environments, the flow regime is the main determinant of channel morphology and habitat features. These include water depth, stream velocity, channel type and shape, and the delivery of nutrients and sediment. The magnitude, frequency, and timing of flow influence in channel and off channel habitat diversity (Abell et al., 2002; Risley, Wallick, Waite, & Stonewall, 2010). Understanding the level of ecosystem structures and functions is essential to establish the freshwater inflows that are needed to sustain the riverine ecosystems.

2.2. Water Resources Management

2.2.1. Sustainable Water Resources Management

Sustainable water resources management involves managing water resources in a manner that ensures the full array of benefits associated with the water and its ecosystem. The aim is to design and implement a management program that stores and diverts water for human purposes in a manner that does not degrade the environment severely. This requires proper understanding of water availability and the influences of human land and water uses in the river basin. This ensures that human impacts on the natural variability of water chemistry and hydrologic processes are constrained within specified limits, as agreed to by water managers and stakeholders (Richter, 2010). As a result the human needs for water are fulfilled while maintaining the composition and functions of the ecosystems and sustaining the services provided by the ecosystems (Richter et al., 2003; Wakitolie, 2013).

Environmental flow studies aim to predict the ecological effects of streamflow alteration triggered by changes in land cover, climate, impoundments, water withdrawals, and similar factors (Carlisle, Falcone, et al., 2010; Murphy et al., 2012; Richter et al., 1996). This provides major contribution to the resolution of conflicts over shared water resources and helps to ensure that societies continue to benefit from the biodiversity and essential ecological goods and services provided by the river ecosystems (Arthington et al., 2006). The Assessment of reliable estimates of ecologically-relevant streamflow characteristics is, therefore, the foundation to the environmental flow studies (Murphy et al., 2012).

2.2.2. Integrated Water Resources Management (IWRM)

Integrated Water Resources Management (IWRM) is defined as: “a process, which promotes the co-ordinated development and management of water, land and related resources, in order to maximise the economic benefits and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.” The three key strategic objectives of IWRM are economic efficiency in water use, equity, and environmental and ecological sustainability. The concept of environmental flows is an essential part of IWRM and plays an indispensable role in achieving the three IWRM objectives (Forslund et al., 2009).

2.3. Streamflow Characteristics

Runoff plays important role in balancing the hydrologic cycle by returning the excess precipitation into oceans and controlling the streamflows. It has also key roles in soil erosion, flooding, and resource distribution. The amount of streamflow from a watershed mainly depends on catchment characteristics (drainage area, soil properties, land cover, topography and vegetation), storm properties (rainfall amount, duration and intensity), characteristics of ground water aquifer, and other climatic conditions. Hence, accurate stream flow estimation is essential for efficient management of watersheds and water resources, flood regulation, and understanding ecological relationships of the river environment (Devia et al., 2015; Sitterson et al., 2012; Tiwari et al., 2013).

Streamflow shapes many fundamental characteristics of ecology and determines the health of riverine ecosystems (Bunn & Arthington, 2002). The overall distribution of streamflow comprises numerous characteristics, including high and low extremes and details of timing and variability of flow conditions (Arthington et al., 2006; Poff

& Zimmerman, 2010). These have significant effects on the structure and functions of the river ecosystems (Bunn & Arthington, 2002; Carlisle, Falcone, et al., 2010; Carlisle, Wolock, et al., 2010; Poff et al., 2010). The incontrovertible ecological effects of Streamflow alterations on impacts of riverine ecosystems include ecological disintegration of floodplain rivers, genetic isolation through habitat fragmentation, and declines in biodiversity and ecosystem services (Cooper et al., 2017; Tharme, 2003).

2.3.1. Flow Regime

Streamflow links the broader landscape to ecological conditions in and near the stream channel. The streamflow characteristics whose alteration is likely to produce significant ecological effects is considered as the flow regime (Arthington et al., 2006). Description of flow regime encompasses the streamflow characteristics in magnitude, frequency, duration, timing, rate of change, and other aspects of hydrologic responses (Knight et al., 2011). Flow regime varies geographically in response to climate and catchment controls on runoff (topography, geology, land cover, position in network). It is often considered in terms of extreme low-flow events, base flows, freshes/pulses, and floods (Speed et al., 2013).

The different components of an environmental flow regime control different ecological processes in the stream ecosystems, which in turn is a major determinant of biotic composition. They provide a driving force in river ecosystems and control key habitat parameters such as flow depth, velocity, and habitat volume. The exchange of organisms, energy, particulate matter, and dissolved substances along the river systems is mediated by the streamflows, floodplain inundations, alluvial groundwater movements, and water table fluctuations (Richter, Baumgartner, Braun,

& Powell, 1998). The flow regime is, therefore, the primary determinant of the structure, composition, and function of riverine ecosystems and the services provided by them (Doyle et al., 2005; Forslund et al., 2009; Poff et al., 2010).

The hydrologic response of streams can be altered by water withdrawal, stream-channel modification, climate change, land use, and other basin-scale factors. As a result, the existing environmental conditions and habitat to which native species have been adapted are disturbed. Additionally, the geomorphic processes on which many species rely for habitat creation and maintenance are modified, thereby disrupting the life stages of native aquatic and riparian species (Bunn & Arthington, 2002). Reduced connectivity between habitats is also another consequence of flow regime alteration (Julian et al., 2015). When natural variability in river flows is altered too much, significant changes in the physical, chemical, and biological conditions and functions of the river ecosystems occur. When changes to natural flow regimes are excessive, the impacts are high to both biodiversity and society (Richter et al., 2003).

A summary of the flow components, flow alterations, and ecological responses is presented in Table 2.1.

2.3.2. Flow Duration Curve

A Flow Duration Curve (FDC) represents the relationship between a given discharge and its corresponding percentage of time that the discharge is equalled or exceeded. It provides graphical view of the overall historical variability associated with streamflow in the river basin. It is one of the most informative methods that show characteristics of the flow regime by displaying the complete range of the river flow. FDC may be constructed using different time resolutions of stream flow data: annual, monthly or daily. Those constructed on the basis of daily flow time series provide the most detailed way of examining duration characteristics of a river (Katuva, 2014). The shape of the flow duration curve strongly reflects the type of flow regime in the river and the characteristics of the upstream catchment. Hence, understanding the FDC of a river assists in providing broad knowledge in hydrologic studies (Sok & Oeurng, 2016).

Table 2.1: Summary of the Flow Components, Flow Alterations, and Ecological Responses

Flow Component	*Flow Alteration*	*Ecological Responses*
Magnitude	Lack of extreme flows and/or greater magnitude of extreme flows	Loss of sensitive species; Reduced diversity; Altered assemblages and dominant taxa; Reduced abundance; Increase in non-natives; Life cycle disruption; Reduced species richness; Altered recruitment; Failure of seedling establishment; Territorialisation of flora; Lower species richness; Vegetation encroachment into channels.
Frequency	Reduced frequency of peak flows	Disrupted/reduced reproduction; Decreased richness of endemic and sensitive species; Reduced habitat for young fishes; Shift in community composition; Reductions in species richness.
Duration	Reduced duration of floodplain inundation	Decreased abundance of young fish; Loss of floodplain habitat; Reduced growth rate or mortality; Altered assemblages; Terrestrialisation of species composition; Reduced area of riparian plant or forest cover.
Timing	Shifts/Loss of seasonal of peak Flows	Disruption of spawning cues; Decreased reproduction and recruitment; Change in diversity and assemblage structure; Reduced riparian plant recruitment; Invasion of exotic riparian plant species; Reduced plant growth and increased mortality; Reduction in species richness.
Rate of change	Increased or reduced variability	Increase in infection; Decreased germination, survival and growth of plants; Decreased abundance and change in species assemblage; Decrease in species richness; Increased abundance of some macroinvertebrate taxa.

Source: Poff & Zimmerman (2010)

2.4. Environmental Flow Assessment (EFA)

According to the Brisbane Declaration (2007), “Environmental flows describe the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems” (Dickens, 2011; Forslund et al., 2009; Poff et al., 2010; Poff & Zimmerman, 2010). Environmental flow is necessary to ensure the existence of habitats in a river (FIU-GLOWS, 2016). It is the flow regime required to achieve desired ecological objectives, to conserve freshwater ecosystems, and to restore the ecological health and functioning of rivers and their associated wetlands for human use and biodiversity conservation (Acreman & Dunbar, 2004; Arthington et al., 2006; Rivaes et al., 2017).

An Environmental Flow Assessment (EFA) is the process of analysing the relationships between ecology and hydrology to determine flows that are required in time and space (Dickens, 2011; Risley et al., 2010; Wakitolie, 2013). It is an assessment of how much of the original flow regime of a river should continue to flow downstream in order to maintain specified values and assets of the riverine ecosystem. This helps to assess the amount of water that can be abstracted from a river without causing significant degradation for the riverine ecosystem (King et al., 2008; Tharme, 2003). Provision of environmental flows is a complex process which requires scientific, economic, political, and social knowledge (Dyson, Bergkamp, & Scanlon, 2003; Perona, Dürrenmatt, & Characklis, 2013; Tharme, 2003; Wakitolie, 2013). It is now widely accepted that a naturally variable flow regime, rather than just a minimum flow, is required to sustain riverine ecosystems (Poff et al., 2010; Poff & Zimmerman, 2010). Therefore, environmental flows should comprise various flow conditions including low flows, average flows, and irregular flooding events (Katuva, 2014).

Environmental Flow Requirement (EFR), produced by EFA, is the description of possible modified hydrological regimes for a river each linked to the predetermined objectives of the ecosystem’s future condition (Tharme, 2003). When assessing EFRs it will be important to select a method that is capable of identifying the key assets or processes within a river, and the specific flows that may be necessary to maintain them. What flow is required for the river to break its banks and to inundate the wetland? How often is this required to support the wetland ecosystem? What flow is required to trigger fish spawning, and at what time of the year? … etc. (Speed et al., 2013). Estimating environmental flow requirements, therefore, requires data on habitat requirements of native biota and the hydrologic, geomorphic, biological, and chemical processes that influence those habitats (Richter et al., 2003).

2.4.1. Methods of Environmental Flow Assessment

EFA is structured, science-based approach that combine hydrological information about a river system with social, physical and biological indicators to determine the sustainable flow levels needed to maintain all components of the river ecosystem (GLOWS-FIU, 2012). A range of methods have been developed in various countries that can be employed to assess environmental flow needs. These methods can be classified into four broad categories: Look-up tables, Desk-top analysis, Functional analysis, and Habitat modelling. The selection of an appropriate environmental flow assessment methodology depends on the availability of data on the river system of concern and existing local constraints in terms of time, finances, expertise, and logistical support (Acreman & Dunbar, 2004; Arthington et al., 2006; Dyson et al., 2003; King et al., 2008; Speed et al., 2013; Tharme, 2003; Wakitolie, 2013).

A. Look-up Tables Methods

Look-up methods define target river flows based on hydrologically defined indices given in look-up tables (Dyson et al., 2003; Tharme, 2003; Wakitolie, 2013). These approaches have been adopted for setting environmental flows and water management rules, to identify permissible alterations, and to determine compensation flows below water retaining structures where few ecological data are available. These methods are easy and cheap to apply, however, they are less accurate and more suitable for scoping studies, reconnaissance level of water resources developments, or as a tool within other methodologies (Acreman & Dunbar, 2004; Speed et al., 2013).

B. Desk-top Analysis Methods

Methods in this section generally focus on analysis of existing data. These are extrapolation methods that use the results of existing field assessments on hydrology and ecology to develop projections of environmental flow needs in a broader suite of river systems (Poff et al., 2010; Speed et al., 2013). An example of a desk-top method is the Range of Variability Approach (RVA) which uses the Indicators of Hydrological Alteration (IHA). Development of the IHA approach concentrates on identification of the natural flow regime components indexed by magnitude, timing, frequency, duration, and rate of change (Acreman & Dunbar, 2004; Richter et al., 1996). Desk-top analysis methods are subdivided into three subcategories as those that use hydrological, hydraulic, and ecological data (Dyson et al., 2003; Wakitolie, 2013).

i. Hydrological Index Methods

Hydrological index methods are desk-top approaches relying primarily on historical flow records to make flow recommendations for the future. All hydrological methods rely on the establishment of relationships, or assumptions about relationships, between flow and geomorphology, water quality and ecology (Speed et al., 2013). Unlike Look-up tables the hydrological desk-top analysis methods examine the whole river flow regime rather than pre-derived statistics. The fundamental principle is to maintain integrity, natural seasonality and variability of flows (Acreman & Dunbar, 2004; King et al., 2008). However, little attention is given to the specific nature of the considered river and its biota (Wakitolie, 2013).

ii. Hydraulic Methods

Hydraulic methods form another group of desk-top analysis that calculates environmental flow requirements by estimating the habitat available during different flows (Speed et al., 2013). There are two main groups of methodologies namely *hydraulic rating* and *habitat rating methodologies.* These methods are founded on a habitat-discharge relationship, which progressively evolved from hydrology, hydraulics and ecology (King et al., 2008; Wakitolie, 2013). *Habitat rating methodologies* assess EFRs on the basis of integrated hydrological, hydraulic and biological response data. These involve detailed analyses of the quantity and suitability of in stream physical habitat under different flow regimes (Tharme, 2003).

Hydraulic rating methods use the relationship between the flow of a river and hydraulic parameters such as velocity, water depth, or wetted perimeter for environmental flow evaluation (Acreman & Dunbar, 2004). The implicit assumption is that ensuring some threshold value of the selected hydraulic parameter at altered flows will maintain the biota and/or ecosystem integrity (Tharme, 2003). These methods are improvements of hydrological index methods, as they require measurements of river channels and incorporate ecologically-based information of the in-stream. However, provision of an acceptable flow is still based more on the physical features of the river rather than on known flow-related needs of the biota (King et al., 2008; Wakitolie, 2013).

iii. Ecological Methods

Desk-top analysis methods that use ecological data are based on statistical relationships between independent variables such as flow and biotic dependent variables. The advantage of these approaches is that they directly address the flow and ecology and consider the nature of the river in question (Wakitolie, 2013). However, it was found difficult to derive biotic indices that are sensitive to flow only. Lack of both hydrological and biological data is often a limiting factor. Time series of ecological data may also be not independent, which can violate the assumptions of classical statistical techniques (Acreman & Dunbar, 2004).

C. Functional Analysis Methods

These methods build understanding of the functional links between several aspects of the river ecosystem and incorporate hydrological analysis, hydraulic rating information and biological data. Expert Panel Method, in this category, uses a team of experts from hydrology, hydraulics, geomorphology, water quality, and ecology for assessing environmental flows (Acreman & Dunbar, 2004; CRC, 2008; Wakitolie, 2013). The Building Block Methodology (BBM) (King et al., 2008), developed in South Africa, is the best known method in this category. The principle of the BBM is that riverine species are reliant on basic elements or building blocks of the flow regime, including low flows, medium flows, and floods. These flow components are provided to fulfil various ecological requirements of a river. A flow regime for ecosystem maintenance is then constructed by combining these building blocks (Acreman & Dunbar, 2004; Dyson et al., 2003; Wakitolie, 2013).

Holistic approaches undertake assessments of a range of different impacts of flow alterations, and develop recommendations for flow regimes on the basis of these assessments (Speed et al., 2013). These methods require collection of considerable specific data from a river and make structured relationships between flow characteristics of the river and the riverine ecosystem (Wakitolie, 2013). The most advanced holistic methodologies commonly utilize several tools from hydrological, hydraulic and physical habitat analysis for establishing the EFRs of the riverine ecosystem (Tharme, 2003). Some holistic approaches also include assessment of the water ecosystems considering all aspects of the hydrological regimes with a fundamental principle of maintaining the natural variability of flows (Acreman & Dunbar, 2004).

D. Habitat Analysis and Modelling Methods

All the three previously described methods have difficulties in relating changes in the flow regime directly to the response of species and communities. Hence methods have been developed that use data on habitat for target species to determine EFRs. The relationship between flow, habitat, and species can be developed by linking the physical properties of the river with the physical conditions of the species (CRC, 2008). Once the relationships between physical habitat and flow are defined, they can be linked to river flow scenarios (Acreman & Dunbar, 2004; Dyson et al., 2003; Wakitolie, 2013). Habitat modelling can perform assessment of multiple species and their developmental stages and provides consideration of flows for sediment transport and channel maintenance. Although this method is expensive to apply, it is suitable for impact assessment of specific sites (Acreman & Dunbar, 2004).

Summary of the different approaches of environmental flow assessment is presented in Table 2.2.

Table 2.2: Comparison of Environmental Flow Assessment Methods

EFA Method	*Sub-types*	*Advantages*	*Disadvantages*
Look-up Table Methods	Hydrological Ecological	Easy and cheap to apply; Rapid to use once calculated; Suitable for scoping and reconnaissance studies.	Not site-specific, less accurate, and hydrological indices not valid ecologically. Ecological indices need region-specific data.
Desk-top Analysis Methods	Hydrological Hydraulic Ecological	Site Specific, examines the whole river flow regime, and incorporates ecologically-based information.	Lack of hydrological and biological data; difficult to derive biotic indices; long time series required; limited flow-biota analysis; time consuming to collect ecological data.
Functional Analysis Methods	Hydrological Hydraulic Ecological	Flexible, robust, more focused on whole ecosystem; make significant use of experts; take a broad view and cover many aspects of the river ecosystem.	Expensive to collect all relevant data and to employ wide range of experts. Consensus of experts may not be achieved.
Habitat Analysis and Modelling Methods	Hydrological Hydraulic Ecological	Replicable, predictive and suitable for specific sites; Relate changes in flow regime to response of species; Assessment of multiple developmental stages and species.	Expensive to collect hydraulic and ecological data and more expensive to apply.

Sources: Acreman & Dunbar (2004); Arthington et al. (2006); Dyson et al. (2003); King et al. (2008); Speed et al. (2013); Tharme (2003); Wakitolie (2013).

2.5. Hydrological Modelling

Hydrological models provide simplified representation of actual hydrologic systems using several equations based on empirical relationships, physical laws, or conceptual operations. They help us to study the functioning of watersheds and their response to various inputs, and thereby gain a better understanding of the hydrologic processes (Gao, Carbone, & Lu, 2018; Tiwari et al., 2013). The two classical types of hydrological models are Deterministic that use direct data and Stochastic that use statistical data. Deterministic hydrology models can be classified as dynamic which include time and static that exclude time factor. Dynamic models are subdivided into event based models that produce output for only specific time periods and continuous models that simulate for longer duration. Commonly used Stochastic models are regression, transfer functions, neural networks and system identification (Moradkhani & Sorooshian, 2009; Nandalal & Ratmayake, 2010).

Hydrologic models have been developed and used to fulfil various desirable needs with a purpose of managing water resources and watersheds (Sok & Oeurng, 2016). Hydrological researchers have developed models and techniques to estimate missing flow data and to reconstruct the time series (Elshorbagy, Panu, & Simonovic, 2000; Tencaliec, Favre, Prieur, & Mathevet, 2015). Various methods have been adopted for infilling missing streamflow data which range from basic interpolations to complex statistical analyses (Mwale, Adeloye, & Rustum, 2012). Hydrological modelling have also been used to simulate the basin’s hydrological process and to estimate the response to various watershed management practices (Choudhari, Panigrahi, & Paul, 2014; Tiwari et al., 2013). These make them as important and necessary tools for the management of water resources, climate change studies, flood prediction, and environmental flow assessments (Devia et al., 2015).

2.5.1. Rainfall-runoff modelling

Rainfall–runoff modelling describes complex surface and subsurface processes of the hydrologic cycle (Kherde, 2016; Moradkhani & Sorooshian, 2009). It involves various parameters that define the characteristics of a watershed and its climatic conditions (Rathod et al., 2015) and sets of equations that describe those processes to estimate the surface runoff generated from the watershed (Devia et al., 2015; Ramly & Tahir, 2016). The various components synthesised are infiltration, soil-moisture storage, ground water percolation, evapotranspiration, surface runoff, and sub-surface flow. Outflow from a sub-basin is computed from rainfall data by subtracting losses, transforming excess precipitations into surface runoff, and adding base flows (Tahmasbinejad, Feyzolahpour, Mumipour, & Zakerhoseini, 2012).

Rainfall-runoff models are generally classified as empirical, conceptual, and physically based models on the basis of the hydrological processes and model input parameters. According to the spatial structure and the extent of physical principles applied to the models, they are categorized as lumped, distributed and semi-distributed models (Beven, 2012; Devia et al., 2015; Sintayehu, 2015; Sitterson et al., 2012).

Empirical or data-driven models are observation oriented models that depend on input data accuracy from statistical relationships between inputs and outputs without considering the features and processes of the hydrological system. On the other hand, conceptual or parametric models describe the hydrological processes using simplified components and equations. Physical based (process-based or mechanistic) models use principles of physics and large number of parameters to describe the physical characteristics of the system. Lumped models do not consider spatial variability of parameters and the entire river basin is taken as one unit. In semi-distributed models, parameters are processed by dividing the catchment into smaller areas. However, distributed models process the spatial variability by using parameters incorporated in high resolution grid cells (Beven, 2012; Devia et al., 2015; Kherde, 2016; Sitterson et al., 2012; Vaze, Jordan, Beecham, Frost, & Summerell, 2012).

Rainfall-runoff modelling may be applied for a variety of design purposes and for providing information to support decision making in water and land management (Mokhtari, Remini, & Hamoudi, 2016). It helps to assess the spatial and temporal catchment yields, to understand the response to climate variability and land use, to understand water availability and seasonal flow characteristics, to estimate and forecast flows, to supplement streamflow data, to infill data gaps, and to assess environmental flows (Devia et al., 2015; Kherde, 2016; Moradkhani & Sorooshian, 2009). Rainfall-runoff modelling involves calibration and validation for simulating streamflows. Calibration is the process of adjusting model parameters to reduce the error between the simulated streamflow and the observed flow record. Model validation uses the calibrated model parameters to estimate runoff for periods outside the calibration period (Vaze et al., 2012).

In addition to good input data, selection of an appropriate hydrologic model is important for good estimation of stream flow from a watershed. Various rainfall-runoff models with different characteristics and applications have been developed to simulate the hydrologic responses of basins (Tiwari et al., 2013). With increased understanding of the hydrological processes and computational technique, rainfall-runoff models have become more sophisticated. Most of the physically-based distributed models have been integrated with the GIS environment (Abushandi &

Merkel, 2013). The choice of an appropriate model, therefore, depends on the purpose of the modelling, nature of the system to be modelled, availability of input data, applicability of the model, and accuracy of the output (Devia et al., 2015; Vaze et al., 2012).

2.5.2. Hydrologic Modelling System (HEC-HMS)

The Hydrologic Modelling System (HMS) is developed by the Hydrologic Engineering Center (HEC) of the US Army Corps of Engineers (USACE). It is designed to simulate various hydrological processes in a wide variety of watershed types. The program has extensive features including graphical user interface with data entry utilities, database, computation engine, and results reporting tools. Tabular and graphical results from multiple elements and simulation runs can be viewed, printed, and stored in the output Data Storage System (DSS) file (USACE, 2016b).

HEC-HMS has four main components; basin model, meteorological model, control specifications, and data input manager (USACE, 2016b). The basin model consists of the elements of the basin and sub-basin that describe the catchment properties. The meteorological model helps to assign the data provided in the data input manager to the hydrologic elements of the basin. The control specifications are used to set the starting and ending dates and the simulation time steps of the rainfall-runoff processes (Bhuiyan, McNairn, Powers, & Merzouki, 2017; Ramly & Tahir, 2016; Sintayehu, 2015).

The watershed model is developed by dividing the hydrologic cycle into various atmospheric and land surface components such as precipitation, evapotranspiration, snowmelt, solar radiation, canopy interception, surface depression storage, infiltration, surface runoff, and base flow. Additional hydraulic components include;

inflows, channel routing, channel losses, diversion structures, and reservoirs. These components are represented by sub basin elements; sources, river reaches, junctions, sinks, reservoirs and diversions (Bhuiyan et al., 2017). They are used to compute the rainfall-runoff processes such as losses, runoff transform, and channel routing using basin characteristics, analysis of meteorological data, and parameter estimation (Choudhari et al., 2014; Mokhtari et al., 2016; Rathod et al., 2015; Thakur, Parajuli, Kalra, Ahmad, & Gupta, 2017).

HEC-HMS can be used to simulate the precipitation-runoff processes of dendritic catchment systems for a broad range of hydrologic problems and diverse water management applications (Thakur et al., 2017). Several studies have used HEC-HMS for rainfall-runoff modelling in a wide range of geographic areas and climatic conditions (Abushandi & Merkel, 2013). Both single event and continuous hydrological modelling can be done to simulate rainfall-runoff processes (Bhuiyan et al., 2017). The model has given reliable results in predicting spatial and temporal watershed responses as well as simulating various scenarios of river flows (Choudhari et al., 2014; Mokhtari et al., 2016; Sok & Oeurng, 2016).

2.5.3. HEC-GeoHMS

HEC-GeoHMS is a Geospatial Hydrologic Modelling extension used for analysing the digital terrain information and processing watershed data which can be used by HEC-HMS to simulate runoff. It works in ArcGIS to develop the physical basin model and prepare a number of hydrologic modelling inputs. It transforms the drainage network and watershed features into a hydrologic data structure that represents the watershed response to precipitation (Nandalal & Ratmayake, 2010; Ramly & Tahir, 2016). HEC-GeoHMS allows to visualize spatial information, document watershed characteristics, perform spatial analysis, delineate sub basins and streams, and prepare hydrologic model inputs that can be used by HEC-HMS (USACE, 2013).

2.6. Ecosystem Functions Model (EFM)

The Ecosystem Functions Model (EFM), developed by the Hydrologic Engineering Center (HEC), is designed for analysing the ecosystem responses to changes in flow regimes of rivers and their connected wetlands. The process of applying HEC-EFM involves three phases: Statistical analyses of relationships between hydrology and ecology, hydraulic modelling, and spatial analyses. In the statistical phase, users identify the water management scenarios (flow regimes) and the aspects of the ecosystem (relationships) to be investigated. Flow regimes are composed of time series of daily mean flow and daily mean stage data that reflect conditions at various locations in the study area. Relationships provide statistical representations that link elements of the ecosystem to the characteristics of the flow regimes through statistical and geographical queries. They offer time series controls that allow users to specify a water year range or an individual water year to be computed. EFM uses combination of expert's knowledge, field data, and scientific literature to define these relationships (Hickey et al., 2015; USACE, 2017).

Statistical Queries (SQ) are defined as combinations of four basic parameters: season, duration, rate of change, and percent exceedance. These define the statistical analysis to be performed for each relationship and offer controls for managing the flow and stage data to be used for the statistical computations. Geographical Queries (GQ) allow users to specify criteria that define relationships from a spatial perspective (Hickey et al., 2015; USACE, 2017). EFM computes statistics that characterize different ecosystem dynamics based on the hydrologic time series and life history requirements of species (Julian et al., 2015). The seasonal, statistical, and spatial results of the EFM process are each informative and useful in their own ways.

Seasonal results are the most direct measure of how ecosystem aspects perform in individual water years and as a progression through time. These results allow habitat suitability to be considered in each water year and correlations to be performed spatially or in terms of habitat areas. Statistical results are pairs of flow and stage data that meet the statistical criteria specified in the relationships. They offer a way to quickly compare alternatives and identify the most effective at achieving project objectives. These results are most useful when many ecological aspects and management alternatives are being considered (Hickey et al., 2015).

HEC-EFM does not have any internal hydraulic modelling capabilities, instead, the statistical results generated by EFM can be simulated with any hydraulic model utilized by the user (Hickey et al., 2015). The Hydraulic modelling, performed outside of EFM, translates the statistical results to water surface profiles and spatial layers of water depth, velocity, and inundation areas (USACE, 2016c). These spatial results provide maps of the areas that satisfy all the statistical and geographical criteria used in the relationships (Hickey et al., 2015).

2.6.1. Applications of HEC-EFM

HEC-EFM is applicable to a wide range of riverine and wetland ecosystems, water management concerns, and restoration projects. It helps to define existing ecologic conditions, identify promising restoration sites, assess ecosystem responses, and compare management alternatives according to predicted ecosystem changes. The statistical and spatial analyses performed by HEC-EFM can be used in actual flow events and in forecast mode to customize hydrographs to produce specific ecological responses (Hickey et al., 2015; USACE, 2017).

EFM can be used to predict responses for a wide variety of flora and fauna by verifying hypotheses that involve hydrology, hydraulics, and ecology. The model is capable of simulating flow regimes for pre and post water resources development projects that change the flow regime or physical characteristics of the river channel. The model can evaluate how changes in flow regime and riverine morphology would impact key attributes of the river ecosystem (USACE, 2017; Wakitolie, 2013). EFM can be used to estimate the effects of past and future flow changes caused by abstraction or dam construction by expressing in terms of usable physical habitat (USACE, 2017; Wakitolie, 2013). This allows for a broader understanding of the individual components of the joint hydrologic alterations in river flows. EFM can also help to connect reservoir operations with field science and monitoring activities (Hickey et al., 2015).

The EFM process can be used to assess factors like water diversions, reservoir reoperations, and climate change scenarios that affect flow without an immediate change in channel topography. The software is generic as it relies on the user to define the aspects of the ecosystem that are of key interest, how those aspects are to be investigated, and which hydrologic, operational, or restoration scenarios to be considered. This flexibility in focus, scale, and scenario is an important and defining aspect of HEC-EFM (Hickey et al., 2015; USACE, 2017).

EFM's strengths include (USACE, 2017):

- ✓ Associating ecology with established hydrologic, hydraulic, and GIS tools;
- ✓ Assessing changes for many flow regimes and ecological relationships;

- ✓ It is quick and inexpensive method that incorporates interdisciplinary knowledge;
- ✓ It is generic software tool which is applicable to a wide range of water and ecosystem management scenarios and restoration projects; and
- ✓ EFM is compatible with other engineering software used in ecological modelling systems.

The key limitations of HEC-EFM include: its use of only daily data, having no explicit tracking of inter-year dynamics, and the outputs are only indicators for ecological attributes (USACE, 2017). EFM is not especially well-suited for use when ecosystem responses are driven by multi-year or multi-event sequences or when sub-daily hydrologic fluctuations are required (Hickey et al., 2015). New features are being added to EFM, EFM Plotter, and GeoEFM that advance their collective ability of analysing flow regimes, generating maps and assessing habitats. Additionally, long-term development will enable HEC-EFM to simulate ecosystems in spatial and temporal needs and to animate results (USACE, 2017).

2.7. Hydraulic Modelling

2.7.1. River Analysis System (HEC-RAS)

River Analysis System (RAS), developed by the Hydrologic Engineering Center (HEC), is designed to perform river hydraulic analyses for networks of natural and constructed channels. It is applicable for performing steady flow water surface profile calculations, one and two-dimensional unsteady flow simulations, movable boundary sediment transport analyses, water temperature and water quality modelling, and several hydraulic design computations. HEC-RAS is designed as integrated software that allows for interactive use in a multi-tasking and multi-user network environment. The system comprises of a graphical user interface (GUI), hydraulic analysis components, data storage and management capabilities, and several reporting facilities. The data files for a project are categorized as: plan, geometric, steady flow, unsteady flow, quasi-steady flow, sediment, water quality, and hydraulic design. All these project components use a common geometric data representation and hydraulic computation functions (USACE, 2016a).

HEC-RAS provides a fully functional modelling environment which allows coping with many problems concerning river networks (Tahmasbinejad et al., 2012). Its main application is to establish water surface profiles along river reaches. In addition to the hydraulic analyses, the system contains several hydraulic design features that can be used when the water surface profiles and spatial layers are computed. The basic computational procedure is based on energy equation that includes losses evaluated by friction (Manning's equation) and contraction or expansion of channels. The momentum equation is utilized in situations where the water surface profiles are rapidly varied. These situations include mixed flow regime calculations, hydraulic jumps, hydraulics of bridges, and evaluating profiles at river confluences and stream junctions. The effects of various obstructions such as bridges, levees, culverts, weirs, spillways and other structures in the flood plain are also considered in the computations (USACE, 2016a). After completing the river hydraulics model, the results can be exported by GeoRAS for processing in the GIS (USACE, 2011).

2.7.2. HEC-GeoRAS

HEC-GeoRAS is an ArcGIS extension specifically designed for processing geospatial data to be used in HEC-RAS and GIS. It helps to create an import file with geometric attribute data from a digital terrain model (DTM) and complementary data sets (Tahmasbinejad et al., 2012). The software provides a set of procedures, tools, and utilities that assist in the preparation of geometric data in GIS for import into HEC-RAS and processing the simulated results of HEC-RAS for analysis in GIS. The water surface profile results can be processed to generate inundation depths and boundaries which facilitates the generation of floodplain maps of the exported RAS simulation results. These post-processing utilities and visualization tools are helpful for understanding and interpreting the results (USACE, 2011).

2.8. Ecosystems of the Umba River

The Umba River Basin includes various ecosystems such as mountains, forests, riparian and floodplain vegetation, wetlands, coastal forests, pastures, agricultural areas, aquatic species, terrestrial animals, and human developments. Although the Eastern Arc mountain blocks contain areas of highest biodiversity in the basin, coastal forests and riparian zones also encompass diverse and important ecosystems. The Umba River estuary supports abundant and diverse ecosystems, the majority of which are located at the end of the river, which makes them susceptible to the effects of flow regime changes. Freshwater flow plays important role in maintaining the estuary that provides essential functions and services to the communities living in the area (VAJIKI PFMP, 2017).

2.8.1. Estuarine Ecosystem

An estuary is an area freely connected to the sea and having freshwater inflow from rivers. It experiences seasonal variations in physical, chemical and biological parameters, driven by the climate, tides, and river flows. Freshwater and saline water inflows influence the properties of water, habitat structure, channel morphology, nutrient compositions, sediment depositions, and productivity of estuaries. This ever changing environment of fresh and saline water is one of the most productive ecosystems. In spite of their importance, however, they are greatly impacted by excessive abstraction of rivers, pollution, habitat alterations, eutrophication, and overfishing. As a result, the natural functioning of these ecosystems continues to be altered causing significant impact on their productivity and provision of ecosystem services (FIU-GLOWS, 2016).

The Umba River estuary is endowed with important terrestrial and aquatic habitats that support rich biological diversity. These include river channel, mangrove forests, seagrass beds, coral reefs, sand dunes and sandy beaches, and other estuarine systems (Mitto et al., 2013; Mocha, 2010). The coastal forests comprise unique communities with high drought resilience and adaptation of flora, endemic birds, mammals, and other fauna. They play a significant role in the hydrological cycle by enhancing soil moisture content, mitigating soil erosion, and connecting to other habitats. They provide shelter, nursery, and feeding areas for a large variety of terrestrial and marine biota (MEWNR, 2013). These provide essential ecological services, support production, and serves as the source of livelihoods and income-opportunities to the communities.

Characterized by the mixing of freshwater and seawater, the estuary depends on the seasonal variations in freshwater inflows. Rainy and dry seasons in the river basin cause these seasonal fluctuations in the freshwater inflows to which local ecosystems have adapted. These have strong influence on the distribution and productivity of the coastal and marine ecosystems (Mitto et al., 2013). However a decrease in freshwater inflow to levels lower than the natural seasonal flow regime results in increased seawater intrusion into the estuary. Decreased river inflows can also lead to decreased nutrient and sediment inputs and disrupted lifecycle processes. Hence, maintenance of a balance between freshwater flows and marine inputs is essential for proper functioning of the ecosystems. This should typically follow the natural seasonal flow variation as seen from long-term historical flow data (FIU-GLOWS, 2016).

2.8.2. Aquatic Ecosystem

Aquatic ecosystems include areas that are permanently covered by water and surrounding areas that are occasionally covered by water. Environmental regimes influence the composition and structure of aquatic communities and continually modify the suitability of the aquatic habitats. These environmental regimes are affected by temporal variations in streamflow, water temperature, dissolved oxygen concentration, transport of sediment and organic matter, and other environmental conditions (Richter et al., 1998). Streamflow provides adequate habitat for aquatic organisms which enables them to move to feeding and spawning areas and to keep their eggs suspended (Risley et al., 2010).

The aquatic fauna of the Umba River include fishes, prawns, crabs and molluscs (Kwale, 2013). The most common families of fish in the area include; Acanthuridae, Carangidae, Coryphaenidae, Gerreidae, Lethrinidae, Lutjaninae, Siganidae, and Sphyraenidae (VAJIKI PFMP, 2017). Individual species have specific requirement on the magnitude of discharge, timing of the flow, temperature, and salinity. Hence, longer duration time series of flow data is required to predict the appropriate flow regime and its seasonal variations. The aquatic animals of the Umba River spawn when the floodplain areas are flooded between October and May. Their eggs require sustained flows for approximately 14 to 28 days before hatching. Favourable spawning conditions need to occur once every two years so that they get a chance to spawn in their lifespan.

2.8.3. Mangrove Forests

Mangrove forests occur along the coast in the intertidal area between the land and the ocean. They are among the most productive ecosystems offering a wide range of resources and services including coastal protection, habitat for diverse flora and fauna, nursery and breeding grounds, source of fire wood, and production of timber, poles, boats and other products (Bosire, Dahdouh-Guebas, Kairo, & Koedam, 2003; Mitto et al., 2013). The mangrove forests have also key roles in climate regulation, carbon cycling, flood and erosion control, filtering and trapping of pollutants, retention of nutrients and sediments, and protecting the beaches and adjacent areas from strong winds and sea waves (FIU-GLOWS, 2016). Other mangrove services include fishing, recreation, extraction of medicines, cultural uses, grazing, and source of fishing gears. They are resource rich environments which promote a variety of food chains and functions playing vital roles for subsistence and livelihoods of the communities (VAJIKI PFMP, 2017). The protection and conservation of these forests is thus important for the continued provision of the ecosystem goods and services.

The mangrove forest of Vanga covers an estimated area of 4,265 ha which is the third largest of the mangrove forests of Kenya. Seven of the ten mangrove species present in Kenya (Wang’ondu et al., 2010) are found in the study area (Table 2.3). Rhizophora mucronata (Rm) and Ceriops tagal (Ct) are the most dominant species making up about 80% of the total forest cover (VAJIKI PFMP, 2017). Freshwater inflows influence the general functioning of the coastal estuary and the seasonal fluctuation of the river flow is adapted by the local estuary. However, when the natural seasonal flow of freshwater is disturbed, the prolonged exposure to seawater elevates stress in mangroves, resulting in increased leaf loss to reduce water loss by transpiration (FIU-GLOWS, 2016; Wang'ondu et al., 2010).

Table 2.3: Mangrove Species Present in the Umba Estuary

S. No.	*Mangrove Species Name*	*Short Name*	*Common Name*	*Salinity Tolerance*
1	Avicennia marina	Am	Mchu	Good salinity tolerance
2	Bruguiera gymnorrhiza	Bg	Muia / Mkifi	Medium salinity tolerance
3	Ceriops tagal	Ct	Mkandaa	Poor salinity tolerance
4	Lumnitzera racemosa	Lr	Kikandaa	Medium salinity tolerance
5	Rhizophora mucronata	Rm	Mkoko / Mrungu / Msisi	Good salinity tolerance
6	Sonneratia alba	Sa	Mpia / Mlilana	Good salinity tolerance
7	Xylocarpus granatum	Xg	Mkomafi / Mronga	Poor salinity tolerance

Sources: Mitto et al. (2013); VAJIKI PFMP (2017)

The phenological events of mangroves depend on the type of species, location and environmental conditions (Okello et al., 2014). However, leaf production is generally higher during the wet season while flowering occurs during the dry months (Wang'ondu et al., 2010). Therefore, mangrove plants need water between November and January to germinate. After germination, seedling survival depends on the rate of stage recession of the flow. Mangrove plants then need continuous inundation after their recruitment season. Therefore, the suitable range of freshwater inflows that maintain healthy mangrove plants of the Umba River should follow the natural seasonal flow variation as seen from the long-term historical flow data.

2.8.4. Riparian Vegetation

Riparian vegetation refers to the trees, shrubs, herbaceous plants, and grasses growing on riverbanks and floodplains. They occupy the stream channel between the low and high water marks and the terrestrial landscape above the high-water mark which is influenced by water level fluctuations. Riparian areas provide habitat for many species, serve as pathways for dispersing and migrating organisms, resources for humans, and contribute in the balance of oxygen, nutrients and sediment (Nilsson & Berggren, 2000). Riparian vegetation are important for reducing erosion, maintaining stability of river banks, retaining and processing overland runoff, providing habitat and food for in stream fauna, canopy cover that mediates water temperature, and serving other ecosystem services (GLOWS-FIU, 2012).

The vegetation along the Umba River is composed of forests, woodland, bushland, grassland, farmland, and swamp vegetation. Some of the common riparian trees include blue gum (Eucalyptus granatum), cashew nuts (Anacardium occidentale), coconut trees (Cocos nucifera), mango trees (Mangifera indica), neem (Azadirachta indica), and whistling pine (Casuarina equisetifolia) (VAJIKI PFMP, 2017). Bushes, shrubs, and other plants and trees are present within the riparian zone covering the river banks and floodplains of the Umba River.

Streamflow maintains water table levels in floodplain and soil moisture which has strong influence on riparian vegetation establishment and recruitment of seedlings. High river flows, on the other hand, prevent encroachment of riparian vegetation to the main river channel. The water flow required for the different riparian vegetation species varies depending on sites and seasons. However, the riparian plants germinate during the short rainy season, between October and January. The rate of stage recession should be as low as possible to enable the seedling survival of the young plants. After their recruitment season, continuous inundation is required from January to March.

2.8.5. Macroinvertebrates

Macroinvertebrates are organisms that lack backbone and are large enough to be seen without magnification. They live for all, or part, of their lives in water and inhabit different types of freshwater environments, from fast flowing streams to slow moving rivers and wetlands. Their common habitats are rocks, leaves, sediments, vegetation, and other materials present in the stream. Examples of macroinvertebrates include crustaceans, insects, molluscs, and worms. They have important role on nutrient cycles, primary productivity, decomposition, and exchange of materials. Macroinvertebrates are also good biological indicators of water conditions and are commonly used to assess the health of streams. Flood flows shape the physical character of river channel and initiate a return to more natural conditions of a river. These trigger new phase of life cycles (Risley et al., 2010) and encourages communities of macroinvertebrates to rebound to their original biodiversity (USACE, 2017; Wakitolie, 2013). Therefore, sufficiently high flow, obtained from the natural flow regime, should flow at any time of the year to maintain balance of the species in the river.

2.8.6. Wetlands

Kenya’s National Wetland Standing Committee defined wetlands as “areas of land that are permanently, seasonally or occasionally waterlogged with fresh, saline, brackish or marine waters at a depth not exceeding six metres, including both natural and man-made areas that support characteristic biota” (Tiner, 2017). Wetlands are generally classified into three main types: *inland wetlands* including permanent and seasonal rivers, inland deltas and floodplains, lakes, ponds and marshes; *marine or coastal wetlands* such as open coast, coral reefs, estuaries, deltas, mangrove forests, and lagoons; and *artificial* or *man-made wetlands* (Mocha, 2010). Wetlands are also classified as marsh, swamp, and bog based on general and nontechnical descriptions (Tiner, 2017). Six classes of wetlands: marine, estuarine, lacustrine, palustrine, riverine, and human made wetlands are present in Kenya (Mocha, 2010).

Wetlands play a fundamental role in maintaining climatic and hydrological stability and supporting huge biodiversity. They are important for downstream flood mitigation, groundwater recharge, retention of sediments and nutrients, and water quality improvement. Natural wetlands also provide life-supporting services by moderating local climate and providing habitat for many aquatic and non-aquatic species (Abell et al., 2002; Mocha, 2010). Many factors affect the availability of water for wetland formation including climate, topography, geology, soils, vegetation, and human activities. On the other hand wetlands can be significantly impacted by water diversions, construction works, forestry practices, agricultural activities, drainage projects, and other human activities (Tiner, 2017).

Every structural and functional characteristic of wetlands are influenced by hydrological regime. The physical, chemical, and biological functions which give wetlands their unique character and habitat value are driven by water availability. Water exchange between rivers and wetland areas plays a key role for maintaining the health of wetlands. The water regime determined by frequency, duration, depth and season of flooding influences the structure and floristic composition of vegetation communities in wetlands. Changes in water level, flooding, and low flows have beneficial effects on the health and productivity of wetlands (USACE, 2017; Wakitolie, 2013). Determining the actual hydrology of wetlands require long-term monitoring of water levels and water tables (Tiner, 2017).

Provision of water flow based on the natural seasonal flow variation as seen from long-term historical flow data can also support the functioning of riverine wetlands. The exchange of water between the Umba River and its floodplain wetlands occur during high flow periods, between September and April. Active exchange of freshwater every 2 years, in this period, can provide healthy conditions to the wetland areas.

2.9. Conceptual Framework

The EFA process is typically developed based on a combination of field studies, literature review, and modelling. In order to maintain the ecosystem functions in their natural state, the historical flow conditions and patterns are required. Different parts of the flow regime are likely to have various environmental and ecological functions. Hence, it is necessary to identify those environmental flow components which are significant to the assets and functions of the river. As part of this process, the hydrology and hydraulics of the river should be investigated to characterize the nature of flow during both low and high flow periods. Once the flow components and river assets are identified, the flows required to fulfil different ecological processes can be determined. Thus, understanding the linkages between the different flow components and assets of the river allows proper planning and effective implementation of the environmental flow assessment process (Speed et al., 2013).

To perform the above stated process, the conceptual framework and modelling processes of the study are summarized as follows (Figure 2.1):

i. Conducting literature reviews on hydrology, hydraulics, and ecology of the river, environmental flow assessment, and modelling;
ii. Collection and analysis of hydrological, hydraulic and ecological data;
iii. Developing a hydrologic model to determine long term continuous time series of daily streamflow;
iv. Investigating the historical flow data of the Umba River and characterizing the ecological links of various communities with the river flow;
v. Setting up a hydraulic model to investigate the relationships between the hydraulic flow characteristics and the natural environmental flows of the river; and
vi. Conclusions from the study and recommendations to be made.

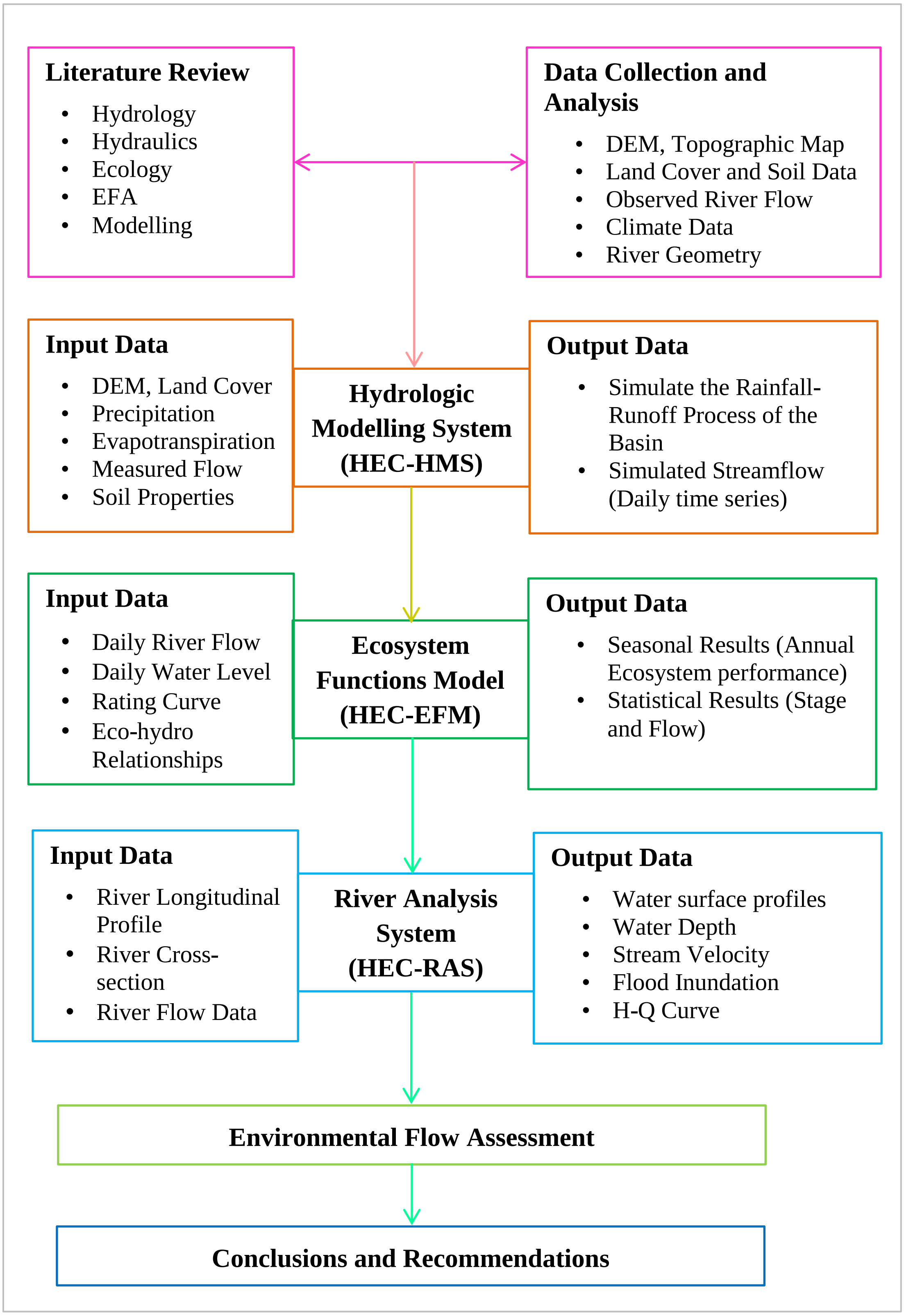


Figure 2.1: Conceptual Framework and the Modelling Processes

2.10. Research Gaps

It is widely accepted that a naturally variable flow regime, rather than just a minimum flow, is required to sustain riverine ecosystems (Poff et al., 2010; Poff & Zimmerman, 2010; Wang et al., 2015). Therefore, variable water releases as close as possible to that of the natural flow regime can be developed. This approach assumes that species are adapted to the natural flow regime of a river and that significant deviations from the natural flow regime will have negative consequences for the species. To estimate the environmental flow needs, the degree to which a river's hydrograph can be altered from its natural hydrograph are characterized and then flows that will reduce the degree of alteration estimated (Bunn & Arthington, 2002; Gorla & Perona, 2013; Richter et al., 1996). However, this approach requires knowledge of the long term historical natural flow regime (Julian et al., 2015).

Management of rivers require scientifically valid set of procedures to implement the allocation of water that meets human demands and in stream, riparian and floodplain needs. Many water allocation processes provide water uses that generally does not favour environmental flow protection, or do not allow for provision of variable flow events for ecological purposes. Implementation of the complicated environmental flow prescriptions that attempt to mimic natural flow variability within water allocation systems has been found very difficult (Richter, 2010).

A study involving quantification of a natural flow regime and its expected deviations was done to evaluate streamflow characteristics. However, the ecological effects of hydrological alteration are still largely unknown, calling for studies that simultaneously assess ecological conditions and hydrological alteration in an effort to better understand how increasingly scarce water resources can be managed to balance the needs of aquatic life and human society (Carlisle, Falcone, et al., 2010).

A research was done to assess the importance of natural streamflow regimes to the maintenance of aquatic communities and ecosystems on a multiregional-scale perspective. The research provided water resource managers with a much-needed perspective on the pervasiveness and severity of anthropogenic alteration of streamflow magnitudes. However, they did not explore the mechanisms underlying the relationships between biological integrity and streamflow alteration, nor was the study design appropriate for evaluating streamflow alteration thresholds that protects biological communities (Carlisle, Wolock, et al., 2010).

The various environmental flow assessment methods depend on identifying a reference condition, usually the natural flow regime, and then determining an acceptable level of alteration without compromising the environmental assets. The method requires sound scientific knowledge for calculating the environmental flow requirements of rivers with different hydrologic or hydraulic characteristics or for achieving different ecological objectives (Speed et al., 2013).

To fill the aforementioned research gaps, it was necessary to understand the historical flow regime and identify the flow components which are significant to the assets and functions of the Umba River. Hence, a hydrologic model was developed to determine long term continuous time series of daily streamflow and to understand the nature of the flow. The ecological links of the historical flow data was then characterized with various communities of the river. Finally, a hydraulic model was developed to investigate the relationships between the hydraulic flow characteristics and the natural environmental flows of the river.

CHAPTER THREE

MATERIALS AND METHODS

3.1. Introduction to Materials and Methods

This chapter outlines the materials and the methodologies adopted in the research study. It gives information about the study area, research design used, data collection procedure followed, methods of data analysis applied, and the modelling processes adopted.

3.2. Description of the Study Area

The Umba River Basin (URB) extends between 3.83° and 4.91° Latitudes, South and between 37.94° and 39.25° Longitudes, East (Figure 3.1). It covers a total area of 8,070 km^2 of which about 5,510 km^2 is in Tanzania and the remaining 2,560 km^2 lies in Kenya. Originating from the Usambara Mountains in Tanzania, the river's main catchment lies in the Tanga region. The river is made up of three main tributaries: Bombo, Mbalamo, and Umba. The combined river drains southeast, crosses the Tanzania-Kenya border, and enters the Indian Ocean through a huge mangrove forest at Vanga town of Kenya. The river flows across an area of widely diverse climate, topography, and land use (IUCN Eastern Africa Programme, 2003; Lerise, 2005).

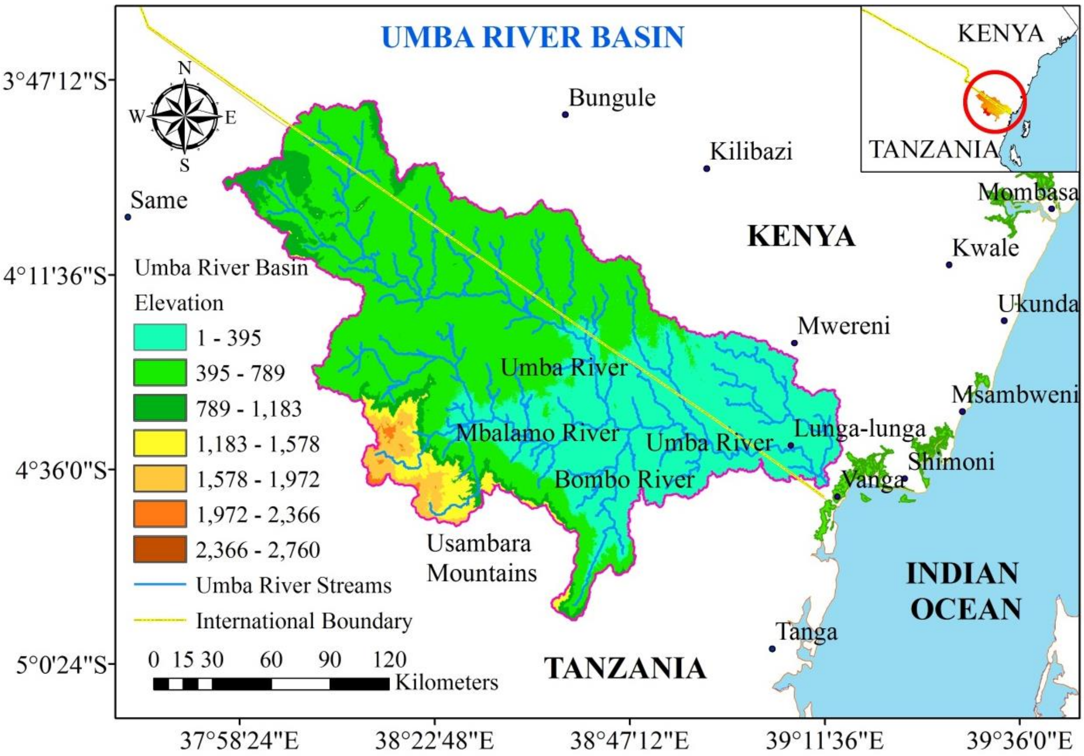


Figure 3.1: Location map showing the Umba River Basin in Kenya and Tanzania

3.2.1. Topography

The topography of the Umba River Basin ranges from sea level at the Indian Ocean to about 2,760 m above sea level at the Usambara Mountains. It comprises five Agro-Ecological Zones (AEZs) namely the coastal plain, the foot plateau, the coastal uplands, the Nyika plateau, and the Usambara Mountains. The coastal plain is found along the coast of the Indian Ocean and extends inland for about 10 km to an altitude of 30 m above sea level. This strip of land is hot and humid and consists of corals, sands and alluvial deposits where crop production and fishing activities predominate. The foot plateau lies at an altitude of between 30 and 150 m above sea level and is sub-humid characterized by a flat plain surface with high potential permeable sand hills and loamy soils. The coastal uplands rise steeply from the foot plateau to an altitude of 500 m above sea level. The Nyika Plateau, also referred as the hinterland, is a semi-arid area located on the north-western part of the basin and lies at altitudes ranging from 500 to 1,200 m above the sea level (CWSB, 2013; Kwale, 2013; MoALF, 2016).

The Usambara Mountains which extend for more than 1,200 m above the sea level are situated in the Lushoto District of the Tanga Region, north-eastern Tanzania. These comprise the easternmost ranges of the Eastern Arc Mountains, separate mountain blocks running from the Taita hills in Kenya to the south-west Udzungwa Mountains in Tanzania, together forming a crescent or arc shape. The range of approximately 90 km long and 40 km wide is one of the world’s Biodiversity hotspots. The Usambara ranges are divided into two sub-ranges, the larger West Usambara Mountains and the smaller East Usambara Mountains. The East Usambara range is closer to the coast and rises sharply which gives rise to the increased rainfall in the southwest of the basin (IUCN Eastern Africa Programme, 2003).

3.2.2. Climate

The Umba River Basin covers humid areas near the Usambara Mountains, sub-humid coastal plains near the Indian Ocean, and semi-arid lands in the north-western part of the basin. The average annual temperature in the study area is 24 °C and the rainfall ranges between 500 mm and 1,500 mm. The highest mean temperatures are experienced in the months of November and April while the coolest period is between June and August. Due to the high mean temperatures across the region the rate of evaporation is high with a mean value of 6.30 mm/day. According to the Köppen–Geiger climate classification system, the basin includes tropical monsoon (Am), tropical savannah with dry summer (As), and tropical savannah with dry winter (Aw). The basin is mainly characterized by tropical climate controlled by the large scale pressure systems of the Western Indian Ocean in combination with orographic effects of the coastal hills and convention over the hot and dry hinterland of the northwest. These result two distinct monsoon periods, with the long rainy season occurring from March to June and the short rainy season occurring between October and January (CWSB, 2013; VAJIKI PFMP, 2017; Wang'ondu et al., 2010).

3.2.3. Land Cover and Land Use

The land cover (Figure 3.2) of the basin is dominated by Mosaic Vegetation and Cropland which covers about 45% of the basin followed by Grassland constituting 20% of the area. The main land uses in the northern part of the basin are irrigation and wildlife conservation, while cattle grazing and irrigation are the main activities in the southern areas (IUCN Eastern Africa Programme, 2003). The water in the Umba River is a critical resource to the livelihoods of the communities living around it for its use in domestic water supply, irrigation, the environment, and other uses. Modern irrigation, which is practiced on the lower part of the river, has a potential for expansion. The Umba river catchment is administered by the Pangani Basin Water Office (PBWO) in Tanzania and the Coastal Development Authority (CDA) and the Ministry of Water Resources and Irrigation for the Kenyan part. The mangrove system in Vanga is under the Kenya Forestry Service (KFS) management (Lerise, 2005).

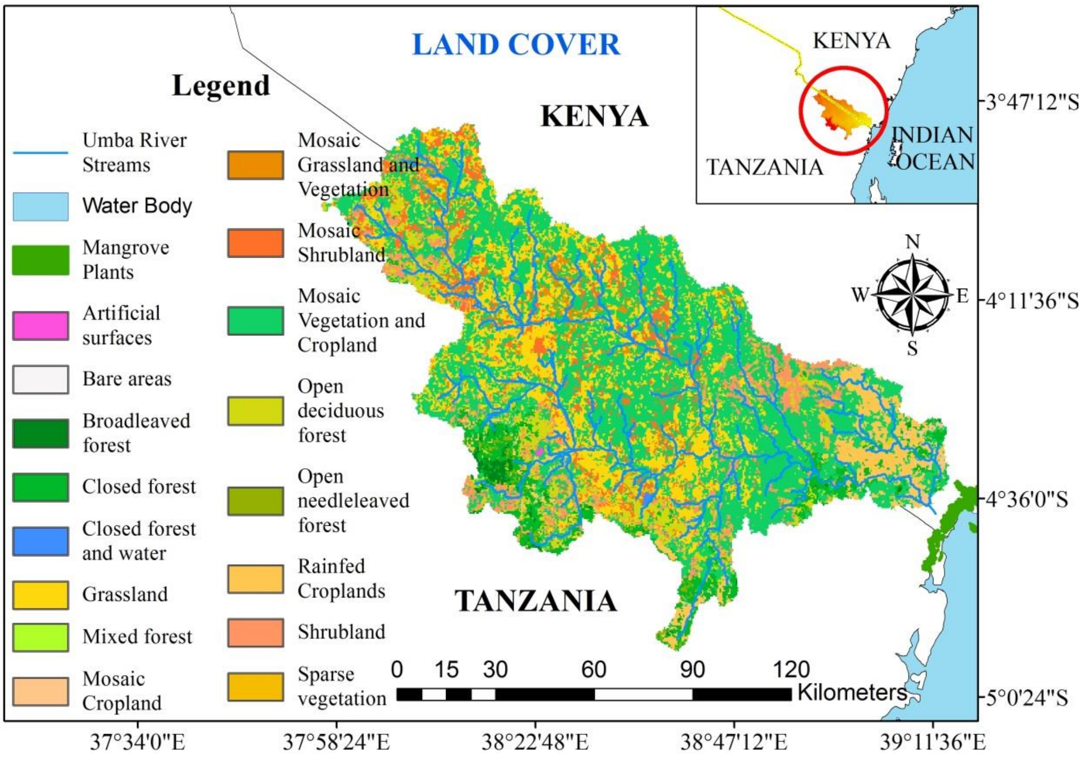


Figure 3.2: Land Cover of the Umba River Basin

Source: (http://www.esa.int/due/ionia/globcover)

3.2.4. Geology and Geomorphology

The soil composition of the basin (Figure 3.3) is dominated by Humi-Rhodic Luvisols, Rhodic Ferralsol, Haplic Acrisol and Chromic Cambisol. The underlying geology of the lower Umba catchment consists of sandstone series, which is highly mineralized (CWSB, 2013). The deposits along the flood plains range from the residual coral limestone in the estuary to columns of sand, clay and rocky outcrops in the upper part of the river. Fine and medium sized sand increase from the upper section to the mouth of river while silt and coarse grained sand decrease (Mitto et al., 2013). The soils vary in structure and texture as a result of the influence of the physicochemical parameters, climatic variations, proximity to the ocean, and the river flow and sedimentation. The principal soil types of the estuary include a narrow strip of coastal sands in the south and bands of red loam and brown clay soils in the north which are generally deep and well drained. The area has fine grained nutrient rich sediments in the estuary where fine grained organic materials settle along with mineral particles (VAJIKI PFMP, 2017).

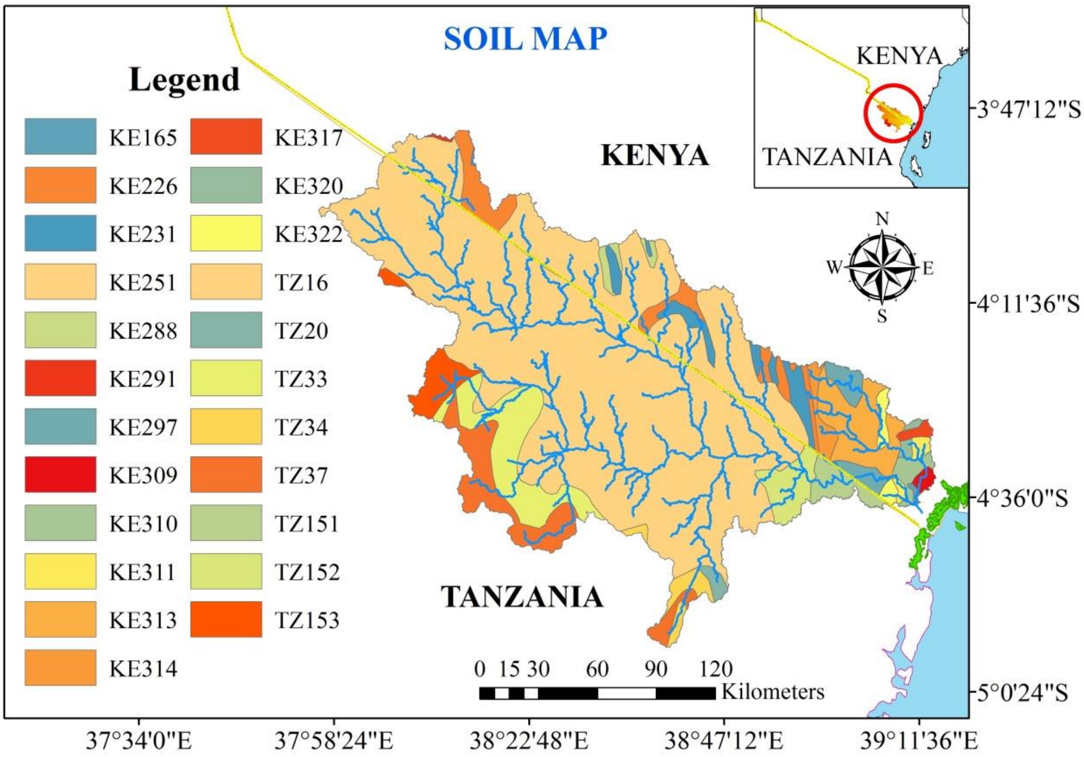


Figure 3.3: Soil Map for the Umba River Basin

Source: (https://www.isric.org/explore/soter)

Description of the Legend is provided in Table 3.1.

Table 3.1: Description of the Soil Groups in the Umba River Basin

Soil Code	Description of Soil Group
KE165	Floodplains. Eutric Fluvisol, Eutric Vertisol, Calcaric Fluvisol and Sodic.
KE226	Plains and uplands. Basement system rocks. Chromic Luvisol, Chromic Cambisol, Petroferric, Haplic Ferralsol and Haplic Luvisol.
KE231	Hills, flat plateau and undulating plains. Basalts and basement system rocks. Lithic Leptosol, Calcaric Regosol and Calcic Gypsisol.
KE251	Plains and footslopes. Basement system rocks. Rhodic Ferralsol, Haplic Acrisol and Chromic Cambisol.
KE288	Footslopes, sedimentary plains and hills. Basement system rocks and Alluvium and colluvium. Haplic Lixisol and Cambic Arenosol.
KE291	Flat plateaus, falt alluvial plains and floodplains. Igneous rocks. Eutric Vertisol and Eutric Fluvisol.
KE297	Plains and uplands. Basement system rocks. Chromic Luvisol, Chromic Cambisol, Petroferric, Haplic Ferralsol and Haplic Luvisol.
KE309	Flat coastal plains, beach ridges, dunes and swamps. Gleyic Luvisol, Umbric Planosol and Rhodic Ferralsol.
KE310	Undulating plains and plateaus. Igneous and metamorphic rocks. Haplic Ferralsol, Rhodic Ferralsol and Humic Ferralsol.
KE311	Plains (uplands), footslopes and ridges. Basement System rocks (gneisses), Haplic Alisol and Haplic Lixisol.
KE313	Hills, flat plateau and undulating plains. Basalts and basement system rocks. Lithic Leptosol, Calcaric Regosol and Calcic Gypsisol.
KE314	Coastal plains. Sedimentary rocks (sandstones) and unconsolidated sediments. Haplic Luvisol, Luvic Arenosol and Chromic Luvisol.
KE317	Lower slopes. Igneous rocks. Humic Nitisol, Luvic Phaeozem. Calcaric Cambisol.
KE320	Mountains and hills. Metamorphic rocks, Eutric Cambisol and Lithic Leptosol.
KE322	Flat lacustrine plains. Sediments. Haplic Phaeozem, Gleyic Cambisol and Calcic Solonetz.
TZ16	Plains and footslopes. Basement system rocks. Humi-Rhodic Luvisols.
TZ20	Plains and uplands. Basement system rocks. Rhodic Ferralsols.
TZ33	Plains and uplands. Basement system rocks. Humi-Rhodic Luvisols.
TZ34	Coastal plains. Sedimentary rocks (sandstones) and unconsolidated sediments. Haplic Luvisols.
TZ37	Middle and upper slopes. Humi-Umbric Acrisols, Humic Andosol and Rhodic Nitisol.
TZ151	Mountains and hills. Metamorphic rocks. Ferralic Cambisols.
TZ152	Flat plateaus, falt alluvial plains and floodplains. Igneous rocks. Grumi-Pellic Vertisols.
TZ153	Plains and footslopes. Basement system rocks. Rhodi-Acric Ferralsols.

Source: (https://www.isric.org/explore/soter), KE = Kenya and TZ = Tanzania.

The lower Umba river reach is narrow and meandering which is confined with wide unconstrained floodplains. The river channel width decreases slightly while the floodplains increase in width as we move from the upper to the lower part of the river. The main river banks are unstable due to the soft soil properties. However, the presence of the riparian trees protects the banks from excessive erosion. The river banks are relatively short which makes the floodplains to be flooded during high flows. The gentle slope of the river results in a stable and riffle flow of water.

3.2.5. Socio-Economic Conditions

The livelihoods of the people living around the Umba River are tightly linked to the environmental services that the river provides. Human water use is dominated by irrigation and domestic uses. The great majority of the population depend on agriculture mainly crop production, livestock rearing, bee keeping, and fishing. Agricultural expansion and harvesting of forest products have increased largely because of population growth and the increased demand for charcoal, fuel wood, and timber. The streams of the basin are also linked to recreational, cultural, and spiritual practices (Kwale, 2013; MoALF, 2016; VAJIKI PFMP, 2017).

The Umba River basin have faced management challenges related to human activities, poor community involvement in conservation, and lack of joint management plans and institutional frameworks. Kenya and Tanzania have signed a Memorandum of Understanding (MoU) for a Joint Cooperative Framework for transboundary management of the Chala and Jipe Lakes and the Umba River ecosystems. The two countries have agreed to cooperate in integrated water resources management; natural resources, environment and ecosystems management;

land use practices; capacity building; data and information sharing; and research and development (Lerise, 2005).

3.3. Rainfall-Runoff Modelling using HEC-HMS Hydrologic Model

The estimation of streamflow along the Umba River was carried out by developing a rainfall-runoff model using the Hydrologic Modelling System (HMS). Watershed and meteorology information were combined to simulate the hydrologic responses. The process involved setting modelling objectives, model selection, data collection and analysis, model development, calibration process, model validation, and analysis and interpretation of the results.

3.3.1. Data Collection Procedure

Topographic map of the study area (scale 1:50,000) was obtained from the Survey of Kenya, Nairobi. A 30m resolution Digital Elevation Model (DEM) of the Umba River basin and its surrounding areas was obtained from USGS (United States Geological Survey) Earth Explorer website (https://earthexplorer.usgs.gov). The catchment characteristics were estimated with the application of GIS, based on the digital elevation data. Land cover of the basin was obtained from GLOBCOVER website (http://www.esa.int/due/ionia/globcover) prepared by European Space Agency - Data User Element (ESA-DUE). Soil data of the basin was obtained from the Soil and Terrain (SOTER) database (https://www.isric.org/explore/soter) of the International Soil Reference and Information Centre (ISRIC).

Rainfall and daily river flow data were obtained from the Water Resources Authority (WRA), Nairobi. The rainfall data were collected from two meteorological stations at Vanga and Mwena. The stream flow data include the observations from the flow gauging station (3KG01) located near Lunga-Lunga. However, the rainfall and daily flow data had missing records and poor areal representation in the basin. Daily measurements on precipitation, atmospheric pressure, relative humidity, air temperature, solar radiation, and wind speed were collected from the National Aeronautics and Space Administration (NASA) for Prediction of Worldwide Energy Resource (POWER) website (https://power.larc.nasa.gov/). The climate data collected covered a time period from January 1981 up to March 2018.

3.3.2. Data Processing and Analysis

Analysis of the streamflow involved checking data record consistency, selection from the available data and establishing operational hydrological parameters for the stream. The data analysis was performed using Microsoft Excel, HEC-DSSvue 2.0.1, and Hydrognomon 4.1. To simulate the rainfall-runoff process of the Umba River Basin, a semi-distributed and continuous hydrological model was developed using HEC-HMS version 4.2.1. The HEC-HMS model was developed with the four main components: basin model, meteorological model, control specifications, and data input manager. In order to simulate the hydrologic processes, the model required various hydrologic parameters of the basin for input to the model components (Ramly & Tahir, 2016; Sintayehu, 2015; USACE, 2016b).

HEC-GeoHMS and Watershed Modelling System (WMS) were used to develop the basin model. The various atmospheric and land surface components of the hydrologic cycle were represented by sub basin elements. The hydrologic elements contain the modelling components that describe canopy interception, surface storage, infiltration, surface runoff, and base flow. The hydraulic components include source inflows, channel routing, channel losses, and outflows. These were represented by sources, reaches, junctions, and sink (outlet). Their principle purpose is to break the watershed into manageable pieces and convert the atmospheric conditions into streamflow at specific locations in the watershed. The basin model, hence, provided the physical representation of the watershed by connecting the hydrologic elements and the hydraulic components in a dendritic network.

The basin model stored the physical datasets describing the catchment properties and was the primary component for visualizing the hydrologic elements and the topology of the stream network that represent the watershed (Bhuiyan et al., 2017). In the process of the hydrologic model development, the spatial distribution information was derived from the DEM of the study area based on WGS 84 - UTM zone 37S. ArcGIS 10.1 was used for the spatial data preparation, to delineate the basin and generate the stream networks. The catchment was sub divided into 11 sub-basins (Figure 3.4) making a semi-distributed model.

The delineation of the watershed and sub-basins was carried out based on the automatic delineation procedure available in ArcHydro and HEC-GeoHMS extensions (USACE, 2013). WMS was then used for extracting the basin characteristics of the river basin such as sub basin features (area, slope, centroid and elevation) and river characteristics (length, slope and centroid). These physical characteristics of the sub-basins and streams were used to estimate the hydrologic parameters of the basin model. By specifying a control point at the downstream outlet (location of the gauging station), the downstream boundary for the HEC-HMS project was defined. Finally, sub-basin and stream data, derived from WMS, were imported to the basin model of HEC-HMS. The resulting hydrologic elements (Figure 3.5) comprise 11 sub-basins, 11 junctions, 10 reaches and a sink (outlet).

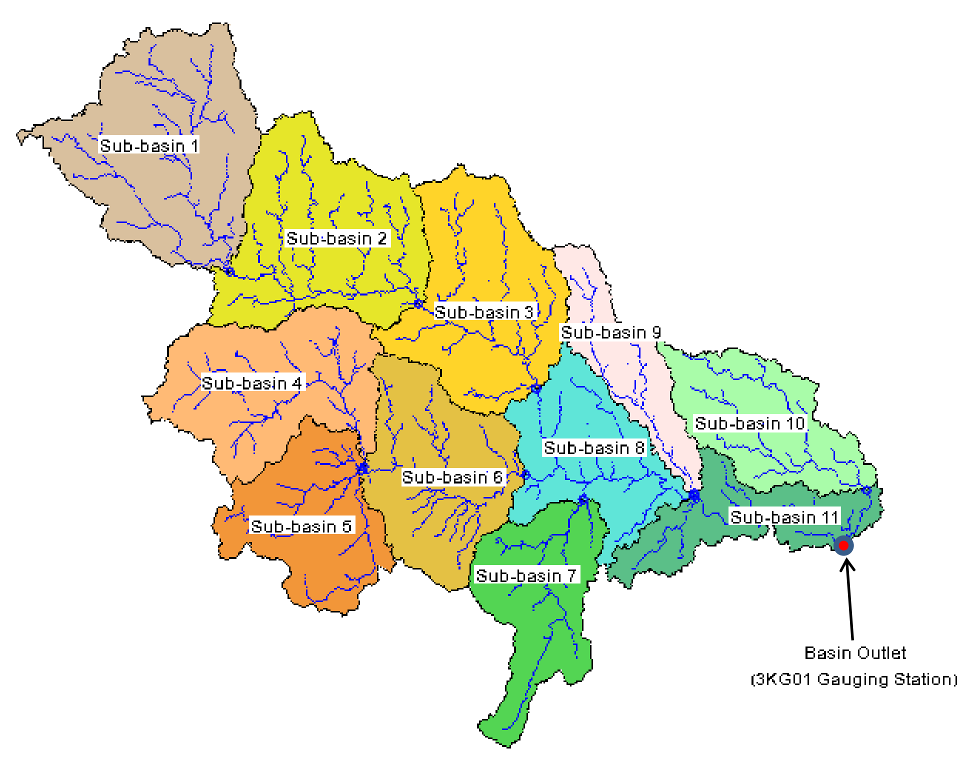


Figure 3.4: Umba River Sub-basins used in the Rainfall-Runoff Modelling

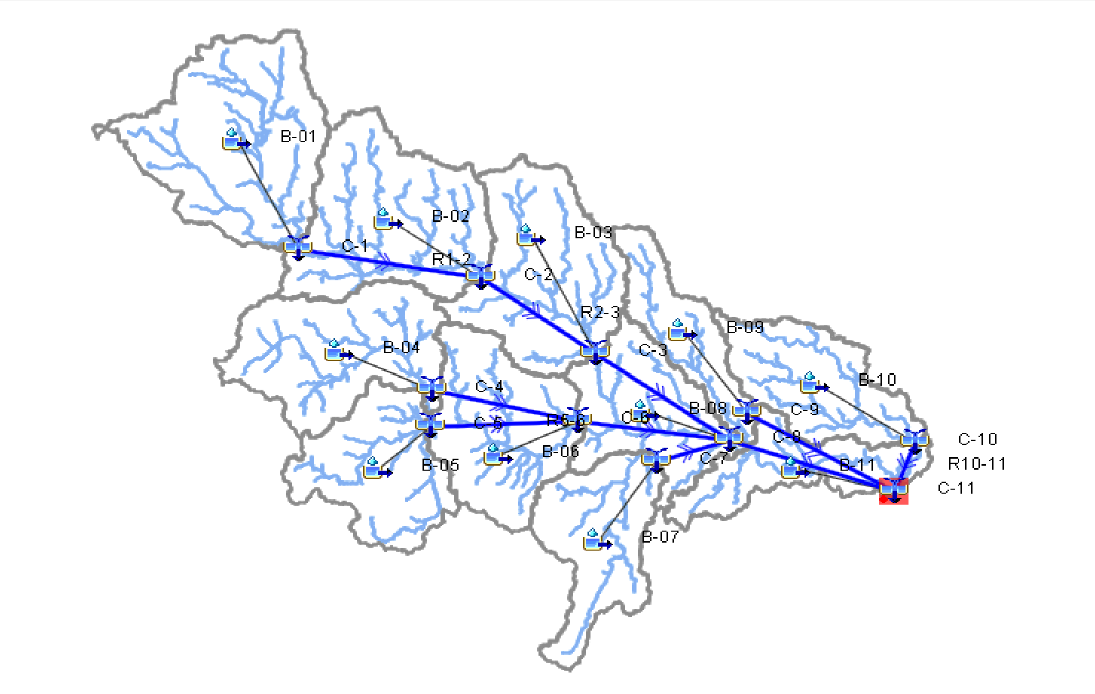


Figure 3.5: HEC-HMS Basin Model Setup for the Umba River Basin (B = sub-basin element, C = junction element, and R = reach element)

The potential evapotranspiration computations were carried out using INSTAT version 3.37 based on the Penman-Monteith method (Stern, Rijks, Dale, & Knock, 2006). Daily precipitation and evapotranspiration of each sub basin and observed river flow data of the basin outlet were then added to the time series data manager component. The meteorological model was then used to define the time-variable boundary conditions of the sub-basins. The precipitation and evapotranspiration data were distributed spatially and temporally over the river basin using the user-specified hyetograph method (USACE, 2016b). The observed flow data was assigned to the outlet of the basin to be used for calibration of the model. The control specifications manager was used to set the starting and ending dates and the simulation time step used in the rainfall-runoff processes. The control times were specified with one day step starting from July 01, 1983 up to December 31, 1985 for model calibration and from January 01, 1986 up to March 31, 2018 for model validation.

Simple Canopy and Simple Surface methods were used to compute water interceptions on the vegetation and the ground surface. In these methods, all precipitations that arrive on plant canopy and the soil surface are captured until their storage capacities are filled. To transform the precipitation into surface runoff, Soil Conservation Survey (SCS) Unit Hydrograph method was adopted. This method provides a generalized unit hydrograph that define the shape of the runoff response using parameters of the flow. In order to evaluate the amount of water subtracted from surface runoff, soil moisture accounting method was used. This method uses three layers; soil storage, upper groundwater, and lower groundwater to represent the water movement dynamics in the soil. Parameters related to moisture conditions of the drainage basin were inserted to the model to calculate the water loss in the three layers. This method is commonly applied with canopy and surface methods in continuous runoff modelling. The Lag routing method was used to describe how the water flows down the river channel. Recession method was adopted to represent the base flow pattern and identification of the base flows and recession rates were done by analysis of the observed flow.

Input parameters that define the geometry of streams and catchment were considered constant during the model simulation. Parameters that determine the state of the catchment and flow domain and that vary during the simulation were optimized (Beven, 2012). The estimation of the state parameters has been carried out with reference to the range of values provided in HEC-HMS. Calibration of the model involved adjusting the model parameter values to improve the match between the simulated results and the observed streamflow records. Automated optimization in conjunction with manual calibration was used to determine the optimum range of the parameter values. The process was conducted by running the model repeatedly and comparing the simulated streamflow results with the observed discharge data at the outlet of the basin (3KG01 gauging station).

Double mass-curve analysis was used to measure the goodness-of-fit between the simulated streamflow and observed records. The slope of the trend line and the coefficient of determination (R^2) were used to assess the model performance. The calibration process was repeated, by adjusting the model parameters, until the values of the trend line and the coefficient of determination approached one. Then a simulation run was created by combining the basin model, meteorologic model, and control specification. The calibrated model, with the best fit parameter values, was used in the validation process. The simulation run calculated the rainfall-runoff response of the basin and provided various graphical and tabular results.

3.4. Analysis of Relationships between Flow Regime and Riverine Ecosystems using HEC-EFM

This study involved statistical analysis of relationships between the historical flow regime and different ecosystem groups of the Umba River. A natural flow regime composed of daily time series of water levels (stages) and discharges was utilized. The functional relationships of the flow regime and the riverine ecosystem were used to develop the eco-hydro relationships.

3.4.1. Data Collection Procedure

The main data required for the model consists of the flow regime and eco-hydro relationships of the riverine ecosystems. Daily water level records and streamflows were obtained from the observed river flow data and the results of the rainfall-runoff modelling. Analysing the streamflow record involved checking data record consistency, selection of record out of the available data and establishing operational hydrological parameters for the stream. These require understanding the way in which flows dynamically change in the river by examining the aspects of flow in magnitude, duration, seasonality, and variability.

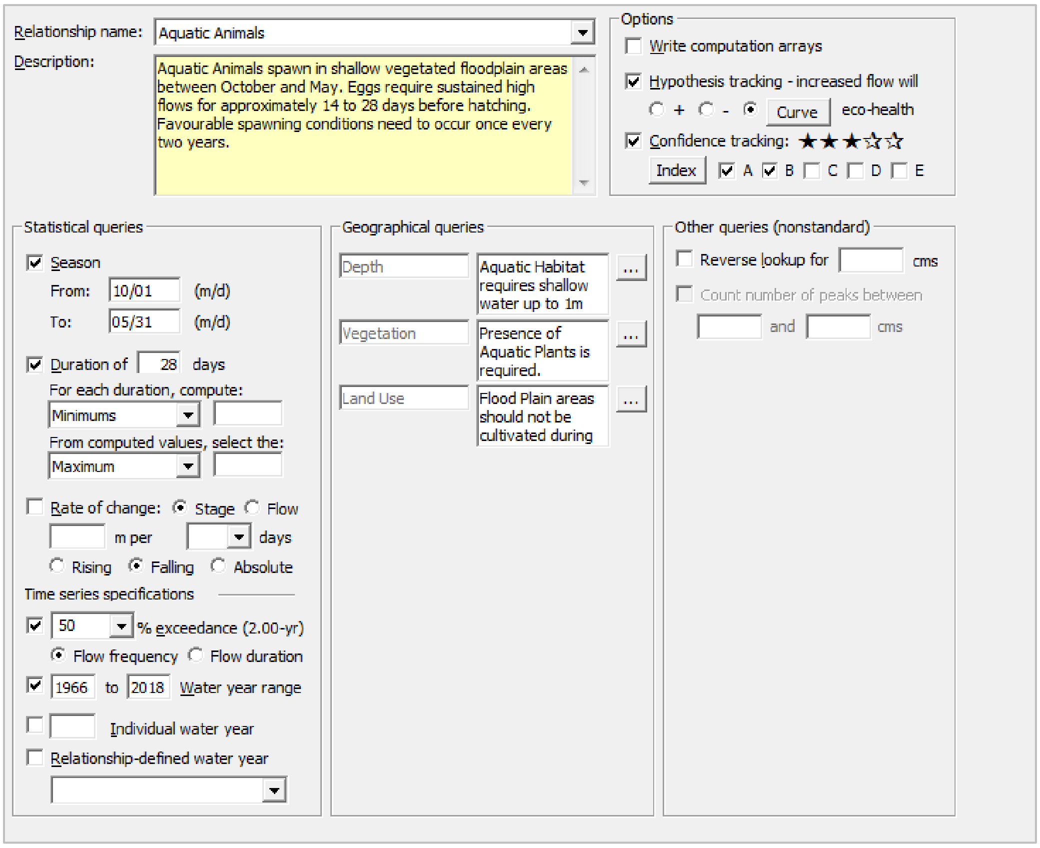
To obtain the best possible level of eco-hydrological information and understanding, an extensive literature review on hydrology and ecology of the study area was conducted. During the field investigation surveys, study sites for assessing the relationship between habitat availability and water discharge were identified. Data regarding the nature of the river, channel shape and pattern, riparian cover, mangrove plants, wetland areas, and other information on the river were gathered (Appendix A). Relationships and life history information were obtained from published references and study reports prepared by Kenya Marine and Fisheries Research

Institute (KMFRI), Vanga Fisheries Department, and Kenya Forestry Service (KFS). The ecosystems were then organised into five groups: aquatic animals, mangrove plants, riparian trees, macroinvertebrates, and floodplain wetlands.

3.4.2. Data Processing and Analysis

HEC-EFM version 3.0 was used to analyse the flow regime of the river and investigate the ecosystem relationships. A stage-flow rating curve, at 3KG01 gauging station, was used to complete the daily time series data of the streamflow using the observed stage obtained from WRA. The same rating curve was also used to compute concurrent time series of water level for the discharge simulated by HEC-HMS. The flow characteristics of the Umba River were interpreted using one day flow-duration curve, monthly flow, and annual flow distributions. Peak flows, mean flows, and discharges with specified durations, seasonal periods, exceedance probabilities, and stage recession rates were then identified. A natural flow regime, composed of the daily time series of flow and stage, was stored in HEC-DSS and imported to HEC-EFM.

Life history information, interpreted in terms of simple statistical criteria, was used to define statistical queries of relationships. This offered control for managing the flow and stage data to be used for the statistical computations. The relationships associate the characteristics of hydrologic and hydraulic time series (flow and stage) with the elements of the ecosystem through combination of four statistical criteria: season, duration, rate of change, and percent exceedance. Habitat preferences were used to specify criteria in geographical queries for defining relationships that investigate biota from a spatial perspective. Figure 3.6 shows sample eco-hydro relationship developed for Aquatic animals of the Umba River.


Relationship name: Aquatic Animals

Description: Aquatic Animals spawn in shallow vegetated floodplain areas between October and May. Eggs require sustained high flows for approximately 14 to 28 days before hatching. Favourable spawning conditions need to occur once every two years.

Options
☐ Write computation arrays
☑ Hypothesis tracking - increased flow will ○ + ○ - ● Curve eco-health
☑ Confidence tracking: ★★★☆☆
Index ☑ A ☑ B ☐ C ☐ D ☐ E

Statistical queries
☑ Season
From: 10/01 (m/d)
To: 05/31 (m/d)
☑ Duration of 28 days
For each duration, compute: Minimums
From computed values, select the: Maximum
☐ Rate of change: ● Stage ○ Flow
m per days
○ Rising ● Falling ○ Absolute
Time series specifications
☑ 50 % exceedance (2.00-yr)
● Flow frequency ○ Flow duration
☑ 1966 to 2018 Water year range
☐ Individual water year
☐ Relationship-defined water year

Geographical queries
Depth: Aquatic Habitat requires shallow water up to 1m
Vegetation: Presence of Aquatic Plants is required.
Land Use: Flood Plain areas should not be cultivated during

Other queries (nonstandard)
☐ Reverse lookup for cms
☐ Count number of peaks between and cms

Figure 3.6: Developing Relationships for Aquatic Animals

In addition to the statistical and geographical queries, relationships were also defined using hypotheses, confidences, and indices. Hypothesis was entered to indicate whether a higher river flow helps, harms, or have a non-linear response for the relationship. Confidences were used for prioritizing the ecosystem relationships. Indices were used to group relationships that have common requirements and to look at the net effect of flow regime changes. After importing the flow regime and developing relationships, statistical computations were performed by HEC-EFM. It analysed the flow and stage time series for the specified criteria and produced flow and stage values for each relationship. The seasonal results for the flow regime and the different relationships were compared using EFM Plotter version 1.1.

3.5. Hydraulic Simulation of Flow Regime using HEC-RAS

This study involved establishing the relationship between the hydraulic flow characteristics and the natural environmental flows for the lower reach of the Umba River. The process involved model selection, data collection, model development, calibration process, model validation, and analysis and interpretation of the results. River geometry and the full range of the flow data were adopted to simulate the hydraulic response.

3.5.1. Data Collection Procedure

The data used to perform the river hydraulics modelling are the river geometry and the flow data. The geometric data consisted of the river system schematic, cross-section data, reach lengths, roughness coefficients, and contraction and expansion coefficients. From site assessments the nature of the river, channel shape and pattern, characteristics of riparian and channel vegetation, and general floodplain conditions were identified. Topographic map of the study area (scale 1:50,000) was obtained from the Survey of Kenya, Nairobi. A 30 m resolution DEM of the Umba River basin and its surrounding areas was obtained from USGS Earth Explorer website (https://earthexplorer.usgs.gov).

Developing the river geometry required high-resolution elevation data to capture the channel and floodplains. However, the river reach alignment and bank locations were not clearly identified from the DEM, hence they were prepared from Google Earth. The river cross-sections were collected by tacheometric surveying on the river (Plate 3.1). The geometric survey was carried out at the river cross-sections using the surveying equipment: total station, GPS, compass, and measuring tape (Appendix B). Since the surveys were conducted during the low flow season, it was possible to access the river bed and cross-section geometry. The river characteristics were further identified by interpretation of satellite images and topographic maps.

Plate 3.1: Surveying at the Umba River near Lunga-Lunga

3.5.2. Data Processing and Analysis

The main steps involved in performing the hydraulic model were geometric data preparation, entering flow and boundary conditions, performing the hydraulic simulation, and analysis and interpretation of results. The river analysis system HEC-RAS version 5.0.3 and its companion HEC-GeoRAS version 10.1 were used for the modelling process. The stream centreline, cross-section lines, river banks, and flow paths were first prepared in Google Earth and imported to ArcGIS for geo-referencing. HEC-GeoRAS was then used to import the geometric data geo-referenced from the Digital Terrain Model (DTM) into HEC-RAS. After importing the river system schematic, additional geometric data were completed to get the physical representation of the river.

The cross-section data, collected from field surveys, were filled to represent the geometric boundary of the stream. After completing the cross-section data, the details of the bridge located near Lunga-Lunga were entered. Levees were specified to some of the cross-sections to prevent flow of water on location other than the river channel. Location of ineffective flow areas were defined at the bridge to define the areas of the cross-sections in which the water will accumulate but not actively conveyed. Initial set of Manning's coefficients were assigned for the channel and floodplains of each cross-sections based on the field data collected from the river.

After providing the geometric data, completion of the hydraulic data was done. Full range of discharge values from the minimum observed flow up to the maximum flow recorded were input to the hydraulic model. Steady flow data was considered for the hydraulic simulation of the river reach. The number of profiles to be calculated, the flow data, and the river boundary conditions were then completed. The normal depth boundary condition was used at the downstream end of the River. The rating curve observed at the gauge location (3KG01) was entered for calibration of the model.

The HEC-RAS model was then run to simulate the runoff and perform water surface profile computations based on the channel morphology and flow data of the river. Different flow profiles were simulated using the hydraulic model and generated water surface profiles, water depth, velocity, and inundation. The model was calibrated by matching the simulated and observed rating curves. The results of the hydraulic simulation were then used for establishing the relationship between the hydraulic flow characteristics and the natural environmental flows.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Introduction

This chapter presents the results and discussion of the research study. The first section describes the analyses of the hydrological data used for the modelling processes. It is followed by the results of the rainfall-runoff model which were developed using HEC-HMS to generate continuous time series of daily streamflow. The third section provides evaluation of the statistical relationships between the historical natural flow regime and different ecosystem groups of the Umba River using HEC-EFM model. Finally, analysis of the hydraulic simulation performed using HEC-RAS model and establishment of the relationships between the hydraulic flow characteristics and the natural environmental flows of the lower Umba River reach is presented.

4.2. Hydrological Data Analyses Results

In order to have an adequate representation of the catchment's water balance, it was necessary to analyse the precipitation, temperature, and evapotranspiration of the basin. The annual average precipitation in the area is 877 mm with a maximum of 1297 mm received in 1997 and minimum of 484 mm recorded in 2003 (Figure 4.1). From the spatial distribution of the rainfall, areas in the southwest of the basin receive higher annual rainfall of about 1030 mm while the areas on the north-western part of the basin receive lower annual rainfall of about 780 mm. The sharp rising of the Usambara Mountains gives rise to the increased rainfall on the southwest part of the basin.

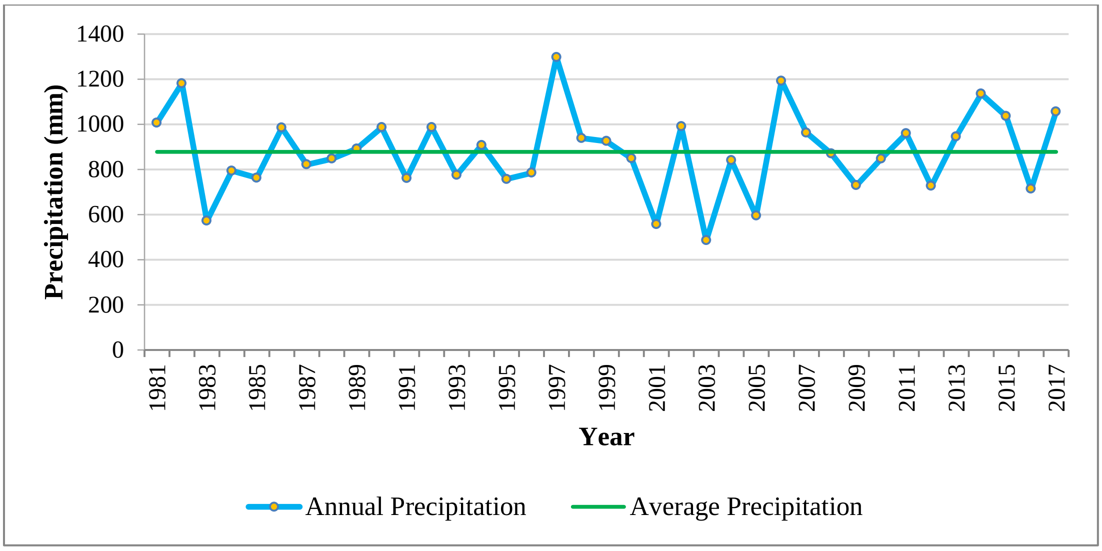


Figure 4.1: Annual Precipitation in the Umba River Basin (1981-2017)

Analysis of the historical rainfall distribution was conducted using Standardized Precipitation Index (SPI), a measure of deviation between a given rainfall value and the overall mean of the rainfall data (Eq – 4.1). SPI can be used to describe rainfall variability and to indicate the number of standard deviations that a rainfall event deviated from the average (WMO-GWP, 2016). The classification for the wetness and dryness of each year was done based on the classification scale given in Table 4.1, as suggested by Hayes et al. (1999). The SPI result, presented in Figure 4.2, indicated that the years 1997 and 2003 were extremely wet and extremely dry respectively. The years 1982 and 2006 were very wet while the years 1983, 2001, and 2005 were very dry. The annual rainfall in 2014 was moderately wet and the remaining years were found having normal rainfall distribution.

$$SPI = \frac{(P_a - P_m)}{\sigma} \tag{4.1}$$

Where: SPI = Standardized Precipitation Index,

P_a = Annual Precipitation (mm),

P_m = Mean Precipitation (mm), and

σ = Standard Deviation (mm)

Table 4.1: Classification scale for SPI values

SPI Values	Category
More than 2.00	Extremely Wet
1.50 to 1.99	Very Wet
1.00 to 1.49	Moderately Wet
-0.99 to 0.99	Normal
-1.00 to -1.49	Moderately Dry
-1.50 to -1.99	Very Dry
Less than -2.00	Extremely Dry

Source: Hayes et al. (1999)

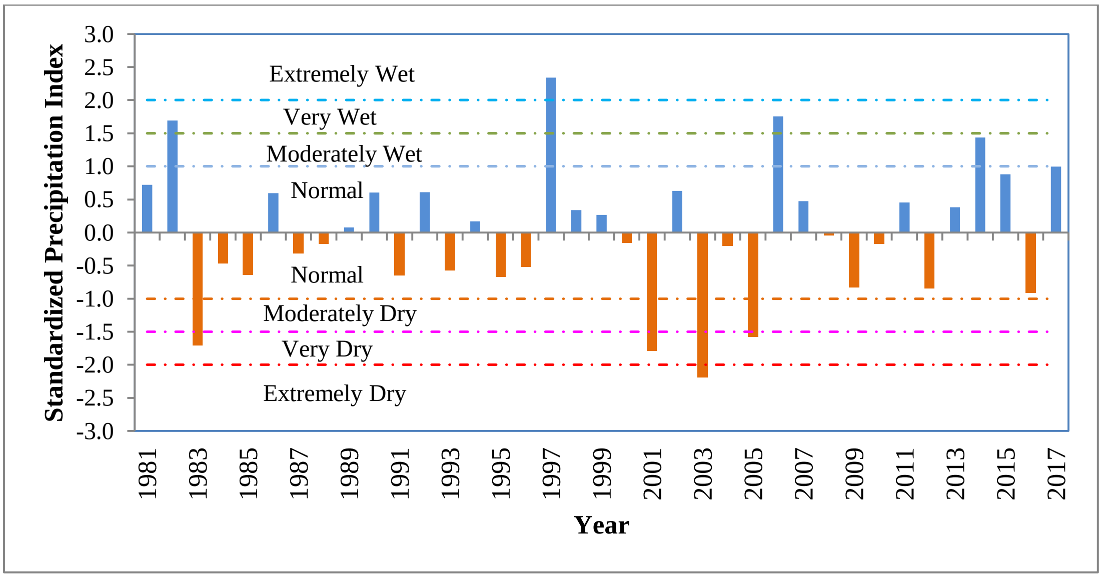


Figure 4.2: Annual Standardized Precipitation Index for the Umba River Basin (1981-2017)

The monthly precipitation (Figure 4.3) of the Umba River Basin indicates that the primary rainy season is from March to May and the short rains fall from October to December. The mean, minimum, and maximum temperatures of the basin are analysed to get an overview of their temporal distribution. The average annual temperature in the study area is 24.21°C with the average maximum temperature of

35.36°C and the average minimum temperature of 14.27°C. Due to the high mean temperatures across the region the rate of evapotranspiration is high with a mean value of 6.30 mm/day. The monthly temperature and evapotranspiration (Figure 4.3) results have similar trends with their values increasing from July up to February and decreasing back up to July.

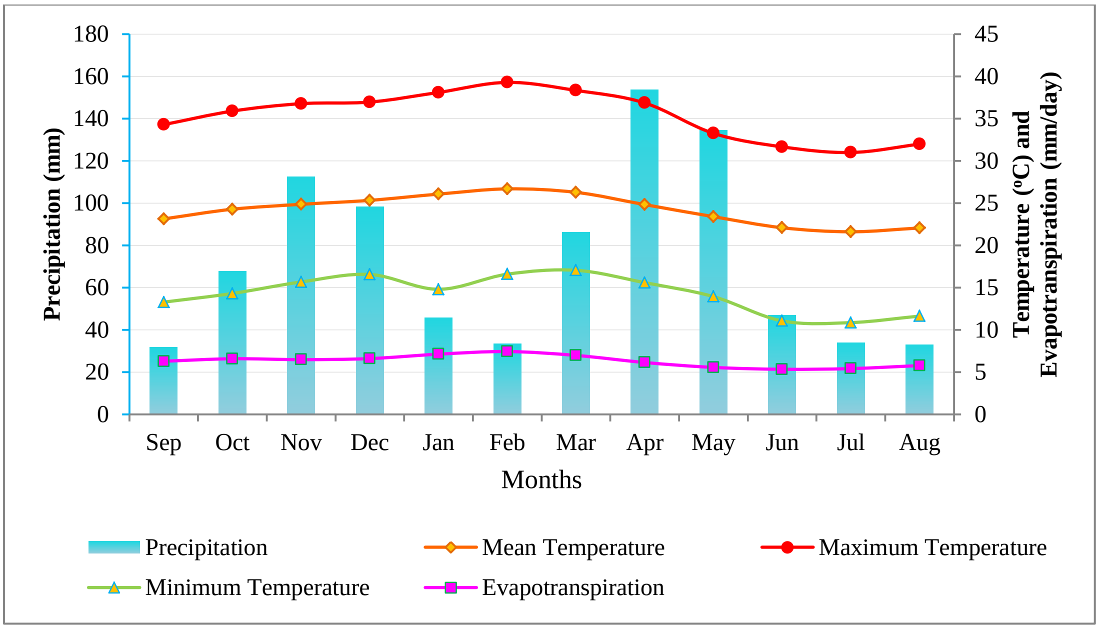


Figure 4.3: Monthly Precipitation, Temperature, and Evapotranspiration in the Umba River Basin (1981-2017)

The Umba River has one flow gauging station (3KG01) on the Kenyan part of the river. It is located on the downstream side of the bridge near Lunga-Lunga (Plate 4.1). The gauging station (Plate 4.2) has four flow gauges with their scales for measuring water level from 0 to 1.5 m, 1.5 to 3.0 m, 3.0 to 4.5 m, and 4.5 to 6.0 m (Plate 4.3). Daily water levels in the river have been monitored at the gauging station since 1966. The stage-flow rating curve (Figure 4.4) was developed by fitting the river flows measured from the gauging station to a rating curve equation using Solver of Microsoft Excel. The goodness-of-fit between the rating curve equation (Eq – 4.2) and the observed data was determined by the coefficient of determination (R^2), obtained as 0.984. The daily discharge of the river was computed from the measured stage using the rating curve equation.

$$Q = 1.64\ (H - 0.054)^{2.8} \tag{4.2}$$

Where: Q = Discharge (m^3/s) and

H = Water Level (m)

Plate 4.1: Bridge at the Umba River near Lunga-Lunga

Figure 4.5 shows the percentage of missing streamflow records. Majority of the available records cover the period from 1966 to the early 1987. In addition to some data gaps existing within the observation period, there is a large period (1988 to 2017) with total missing or high percentage of missing flow records. To infill the missing records and estimate the streamflow from the basin a rainfall-runoff model was developed using HEC-HMS.

Plate 4.2: Flow Gauging Station (3KG01) located on the downstream side of the Bridge near Lunga-Lunga

Plate 4.3: Four Flow Gauges of 3KG01 Gauging Station with their scales for measuring Water Level 0 to 1.5m, 1.5 to 3.0m, 3.0 to 4.5m, and 4.5 to 6.0m

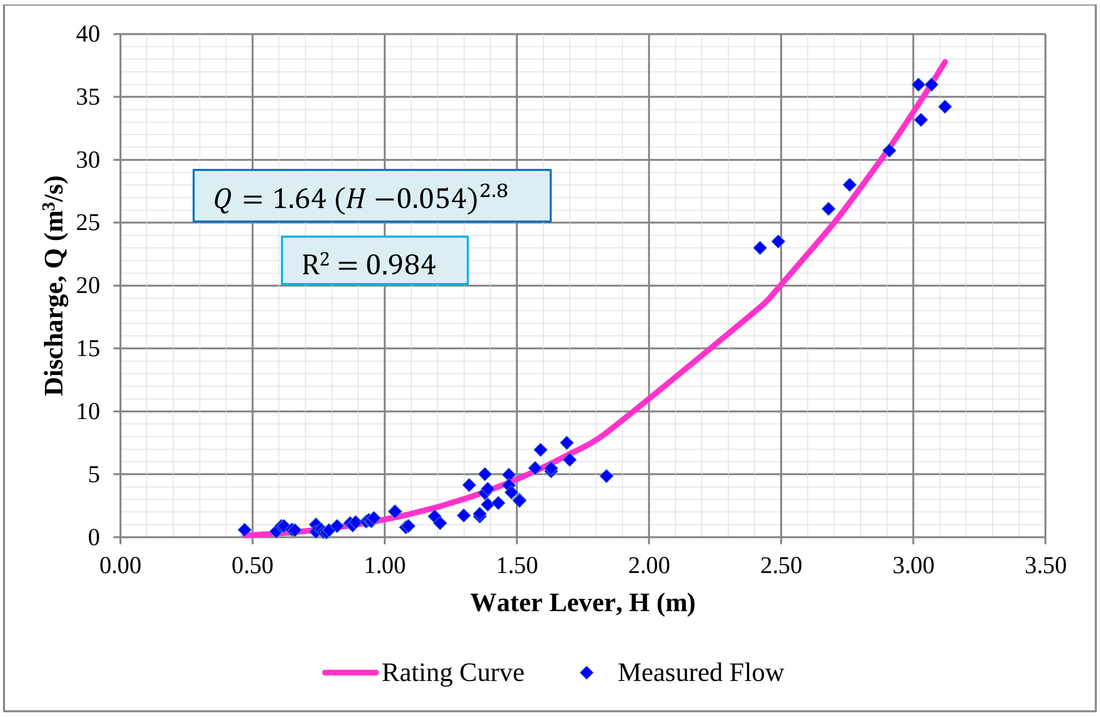


Figure 4.4: Stage-Flow Rating Curve for 3KG01 Gauging Station located near Lunga-Lunga

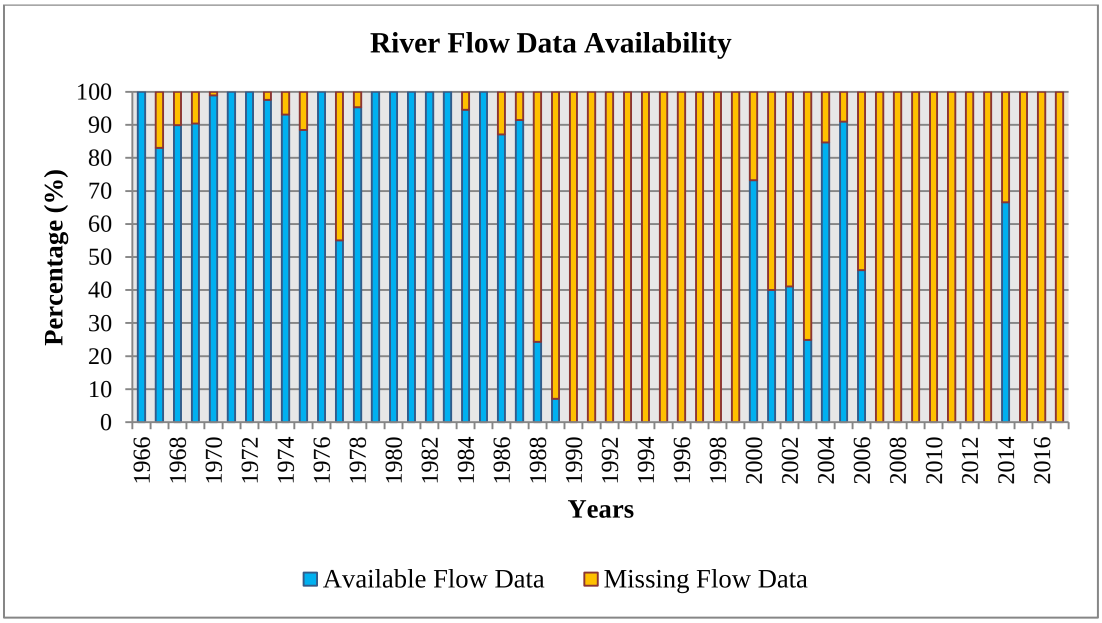


Figure 4.5: River Flow data availability for 3KG01 Gauging Station

4.3. Rainfall-Runoff Modelling Results

The rainfall-runoff model developed using HEC-HMS was used to produce an estimate of the streamflow from the Umba River basin. Hydrological parameters such as precipitation, evapotranspiration, catchment characteristics, and soil properties were input to each sub-basin. The catchment and stream characteristics extracted from WMS are presented in Table 4.2. These physical parameters define the geometry of the sub-basins and streams in the basin model.

Table 4.2: Catchment and Stream Characteristics of the Umba River Basin

Sub-basin	Average Area (km^2)	Sub-basin Slope (%)	Mean Elevation (m)	Centroid Stream Distance (km)
1	968.58	9.40	730.06	33.65
2	855.07	8.74	613.04	35.48
3	786.66	10.26	503.87	24.24
4	729.85	13.46	618.47	32.63
5	556.45	26.85	1167.59	13.88
6	664.00	9.64	421.83	28.23
7	519.62	13.63	423.16	26.84
8	538.67	10.19	271.80	29.66
9	346.15	14.16	363.40	33.74
10	510.65	12.70	156.10	31.73
11	409.69	11.59	119.40	33.89

Parameters that determine the state of the catchment and flow domain and that vary during the simulation were optimized during the model calibration process. Table 4.3 presents the state parameters of sub-basin 1 optimized during the model simulation. These parameters were used to estimate the losses by canopy interceptions, surface storages, infiltrations, and ground water percolations, to transform the precipitation into surface runoff, to describe the water flows in the river channels, and to represent the base flow patterns. Similar results were obtained for all the other sub-basins.

Table 4.3: State Parameters of Sub-basin 1 Optimized during the Simulation of the HMS Model

S. N.	Parameters	Units	Minimum Value	Maximum Value	Optimized Value
1	Simple Canopy - Initial Storage	%	0.001	100	0.12
2	Simple Canopy - Max Storage	mm	0.01	1500	3.48
3	Simple Surface - Initial Storage	%	0.001	100	0.30
4	Simple Surface - Max Storage	mm	0.01	1500	12.50
5	Soil Moisture Accounting - Initial Soil Content	%	0.001	100	5.86
6	Soil Moisture Accounting - Initial GW1 Content	%	0.001	100	18.06
7	Soil Moisture Accounting - Initial GW2 Content	%	0.001	100	55.06
8	Soil Moisture Accounting - Max Infiltration	mm/hr	0.01	500	8.68
9	Soil Moisture Accounting - Soil Storage	mm	0.01	1500	78.75
10	Soil Moisture Accounting - Tension Storage	mm	0.01	1500	56.64
11	Soil Moisture Accounting - Soil Percolation	mm/hr	0.01	500	8.06
12	Soil Moisture Accounting - GW1 Storage	mm	0.01	1500	98.66
13	Soil Moisture Accounting - GW1 Storage Coefficient	hr	0.01	10000	23.26
14	Soil Moisture Accounting - GW1 Percolation	mm/hr	0.01	500	11.26
15	Soil Moisture Accounting - GW2 Storage	mm	0.01	1500	264.06
16	Soil Moisture Accounting - GW2 Storage Coefficient	hr	0.01	10000	46.46
17	Soil Moisture Accounting - GW2 Percolation	mm/hr	0.01	500	26.46
18	SCS Unit Hydrograph - Lag Time	min	0.01	1440	164.16
19	Recession - Initial Discharge	m^3/s	0.01	100	1.12
20	Recession - Threshold Discharge	m^3/s	0.01	100	1.29
21	Recession - Recession Constant		0.01	1	0.82
22	Lag - Lag	min	0.01	1440	200.14
23	Constant - Flow Rate	m^3/s	0.01	100	0.59
24	Constant - Fraction		0.001	1	0.19

The outflow from the basin was computed from the rainfall data by subtracting the losses, transforming the excess precipitations into surface runoff, and adding the base flows. The combined hydrographs for the daily observed flow data (measured at 3KG01 gauging station) and the daily simulated results computed from HEC-HMS are presented in Figure 4.6. From the graphical comparison of the simulated and observed hydrographs, more peak flows are generated by the model.

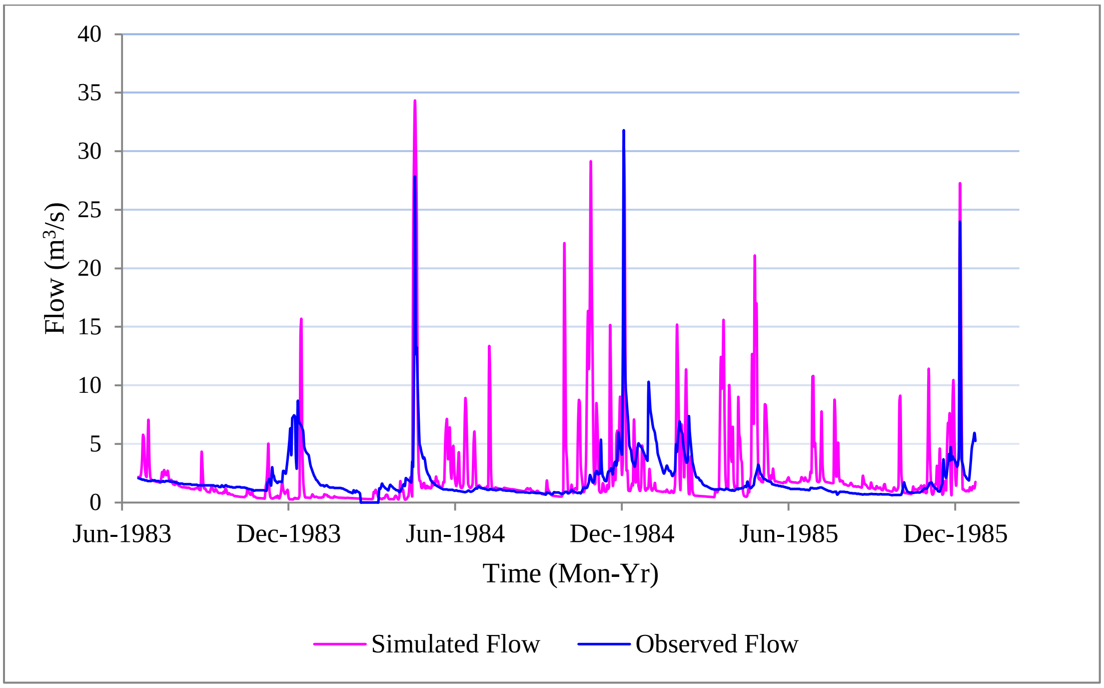


Figure 4.6: Daily Observed and Simulated Time Series for Model Calibration using HEC-HMS at 3KG01 Gauging Station

The quantitative measure for the goodness-of-fit between the computed outflow and observed streamflow was done using the monthly mass-curve (Figure 4.7). After the last optimization trial, the slope of the trend line and the coefficient of determination (R^2) are determined as 1.16 and 0.96 respectively. These values were used to evaluate the overall performance of the model for the calibration period (1983 to 1985) and it was found satisfactory. Points plotted on the 45-degree line (slope = 1) indicate the computed flow is exactly equal to the observed flow. However from the analysis, the slope of the trend line is more than 1 which tells the simulated flow is higher than the observed flow. The coefficient of determination has provided a statistical measure of how close the computed outflow and observed streamflow are to the fitted regression line.

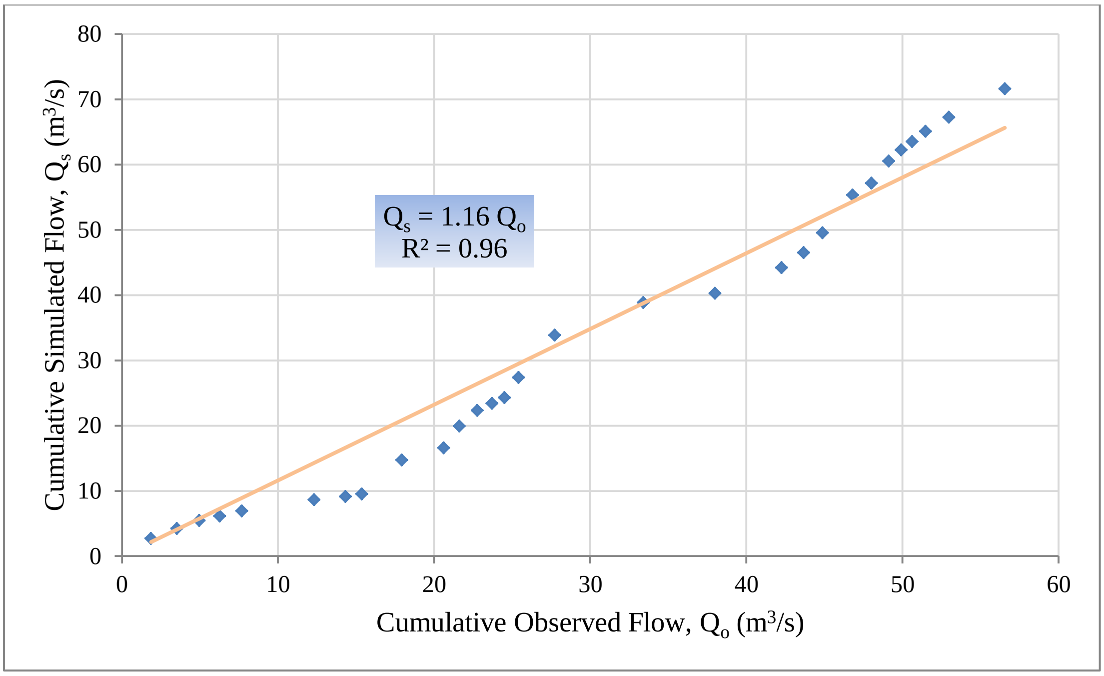


Figure 4.7: Double Mass-curve for Flow Comparison of the Simulated and Observed Flows during Model Calibration at 3KG01 Gauging Station

The optimized parameter values obtained during the model calibration process were used for simulation of the rainfall-runoff response of the basin in the validation period. The simulation was performed to estimate the discharge for infilling the missing records and to extend the flow data of the river. Daily time series of discharge of the Umba River basin was estimated for the entire duration of the validation time defined in the control specification. As shown in Figure 4.8, the daily simulated flow covers for the period of 01/01/1986 to 31/03/2018 and the daily observed flow is distributed from 01/01/1986 to 30/11/1987.

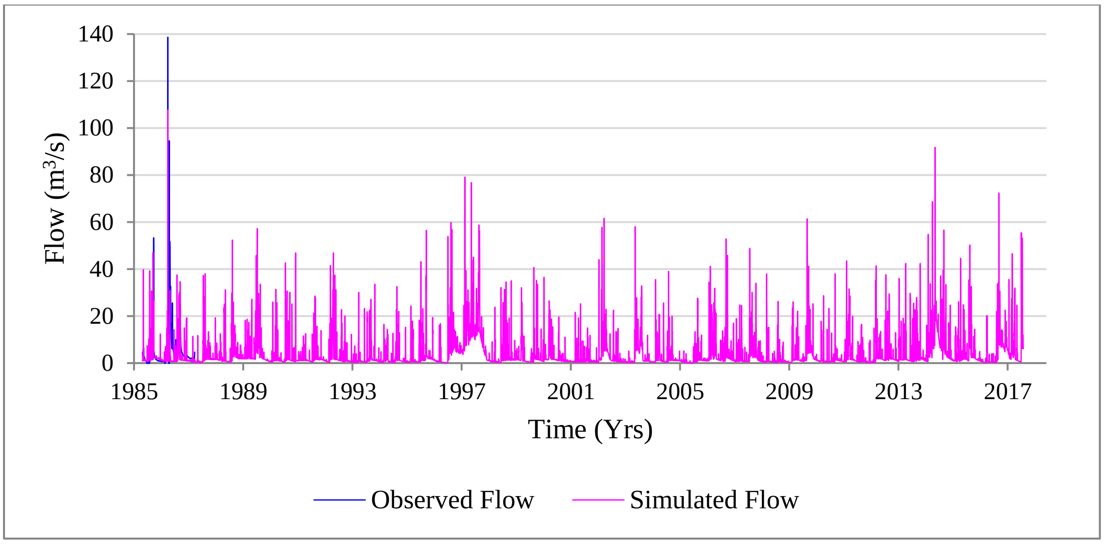


Figure 4.8: Daily Observed flow and Simulated Streamflow Model Validation using HEC-HMS at 3KG01 Gauging Station

The quantitative measure for the goodness-of-fit between the computed outflow and observed streamflow was done using the monthly mass-curve (Figure 4.9). The slope of the trend line and the coefficient of determination (R^2) are determined as 1.16 and 0.94 respectively. These values were used to evaluate the overall performance of the model for the validation period (1986 to 2017) and it was found satisfactory. The results of the model and the measured flow records were used for investigation of the flow regime, hydraulic modelling and assessment of the environmental flows in the river.

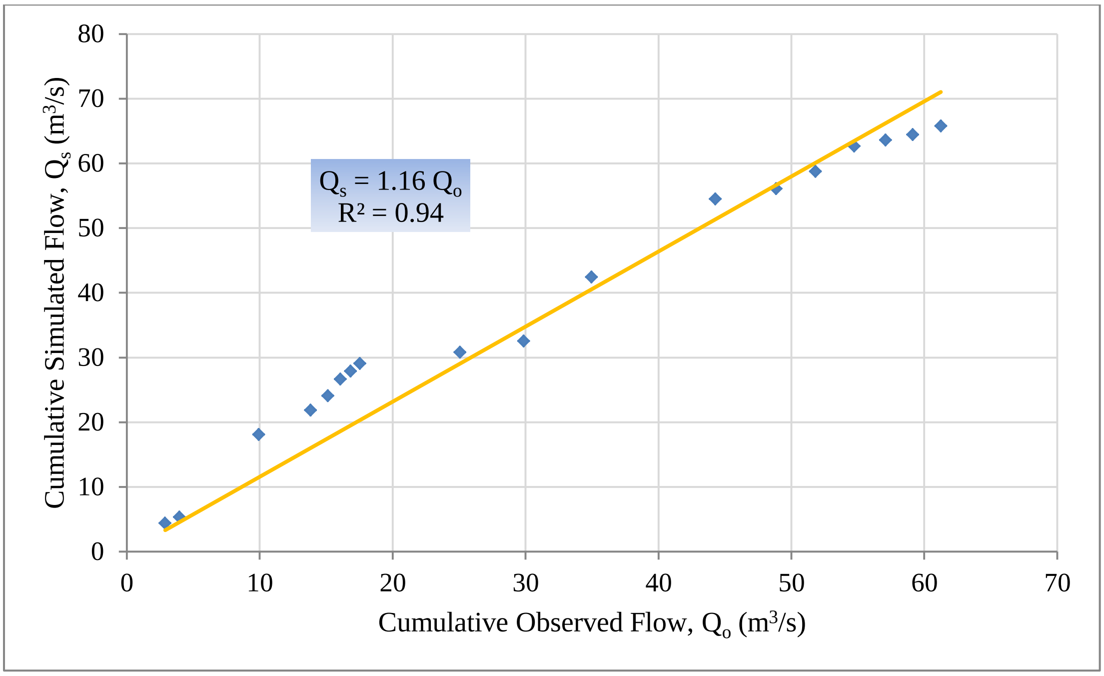


Figure 4.9: Double Mass-curve for Flow Comparison of the Simulated and Observed Flows during Model Validation at 3KG01 Gauging Station

The HEC-HMS hydrologic modelling approach was adopted to generate the continuous time series of daily streamflow for the last 30 years. This study indicates HEC-HMS can be applied to simulate continuous river flows that can be used to evaluate hydrologic flow regimes and environmental flows. The hydrographs created by the program can be used for studies of water availability, flow regulation, and other water management plans. The hydrological model is helpful to understand the hydrological processes with the help of spatial and temporal data of rainfall, catchment characteristics and other climate data (Gao et al., 2018).

4.4. Analysis of Relationships between Hydrology and Ecology

The river flow observed at 3KG01 gauging station was combined with the streamflow data simulated by HEC-HMS to prepare daily time series of river flow. These historical flow data of the Umba River was investigated to understand the seasonal variability in flow that the estuarine ecosystem has experienced in the past 50 years. The mean annual flow of the river, for the entire flow period of 1966 to 2017, was found to be 4.41 m^3/s. During this time period, the maximum ever recorded flood was 221.61 m^3/s and the lowest flow was 0.07 m^3/s. The river flow was further analysed to investigate the flow distribution in each month (Figure 4.10) and to understand the seasonal and inter-annual variability of the flow that the estuarine ecosystem has adapted over the time.

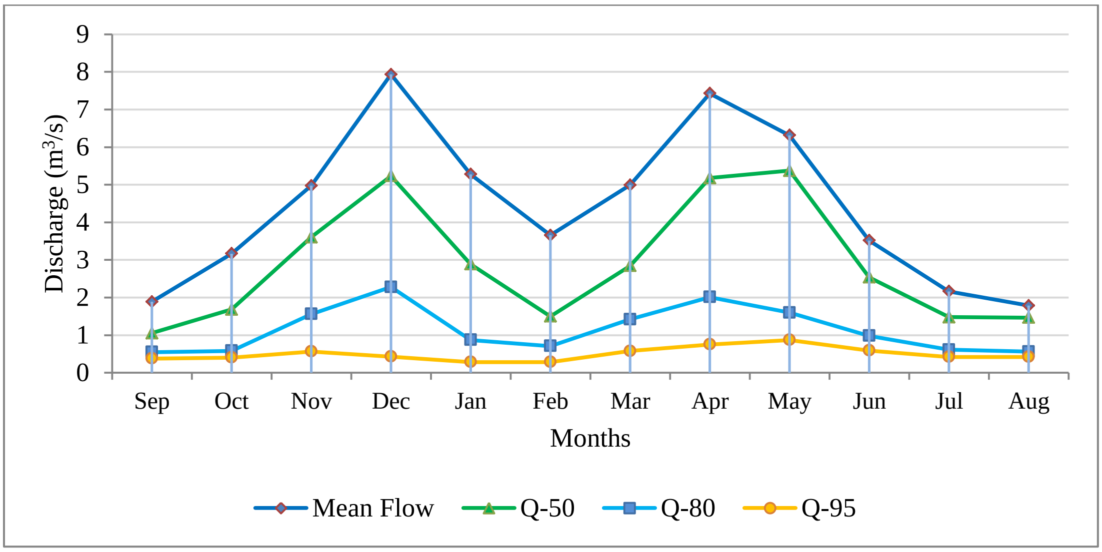


Figure 4.10: Mean Monthly Flow, 50%, 80% and 95% Exceedance Flows at 3KG01 Gauging Station (1966 - 2017)

The monthly flow pattern indicates a seasonal trend with low flows experienced during the dry periods (June to October and February) and high discharges flowing during the rainy seasons (November to January and March to May). The flow of the river is characterized by high seasonal variability due to the seasonal variations in the climate. The ecosystem in the river and estuary has evolved with this variability of flow over the years. This is an important aspect to be kept in mind while managing water abstractions and maintaining flow within the river. The graphs of Q-50, Q-80 and Q-95 represent the flow values exceeded by 50%, 80% and 95% of the monthly flows respectively. The annual distribution (Figure 4.11) of the streamflow shows the historical flow characteristics of the Umba River. The years 1978, 1979, 1997, 1998 and 2015 had higher flows compared to the other years. Most of the remaining years have experienced flows near the overall average of 4.41 m^3/s.

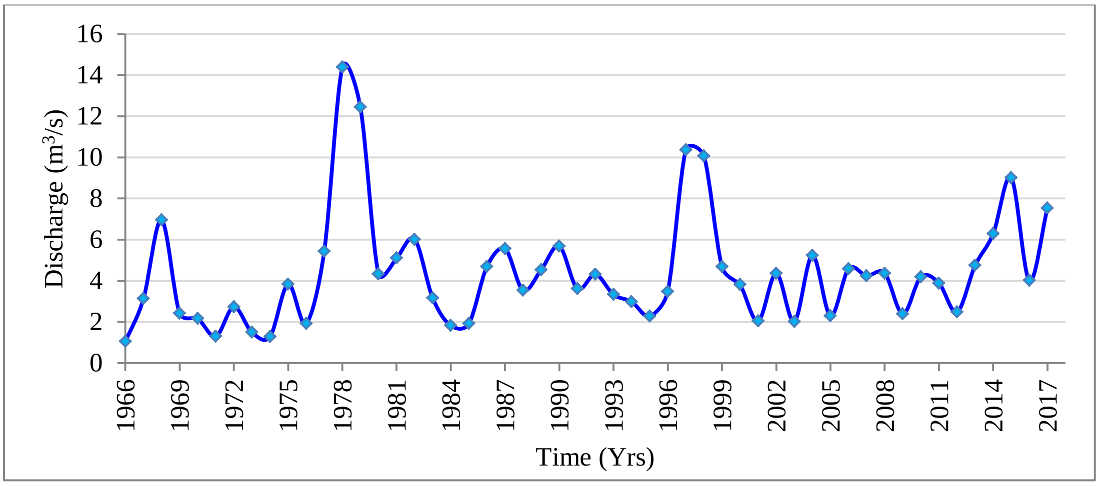


Figure 4.11: Mean Annual Flow of the Umba River at 3KG01 Gauging Station

A daily flow duration curve (FDC) was prepared by arranging the daily discharge in descending order. The percentage of time that each discharge is equalled or exceeded was then calculated using the Weibull formula (Chow, Maidment, & Mays, 1988). The FDC (Figure 4.12) has indicated the flow variability at the basin outlet by displaying the complete range of the river discharges from low flows to flood events. The graph shows very steep slopes for the extreme low and high flows indicating that few flow events were experienced for those flows.

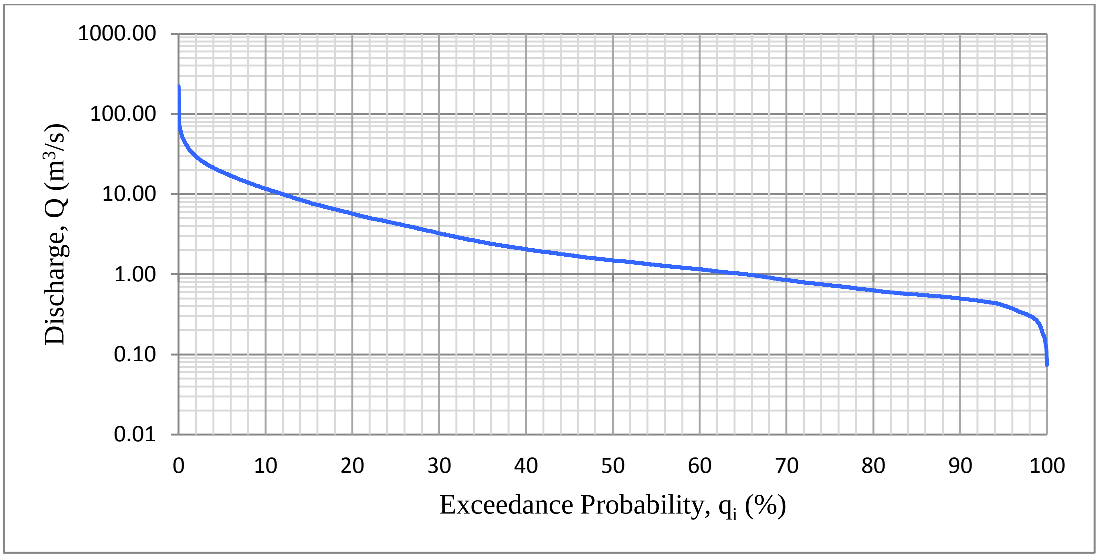
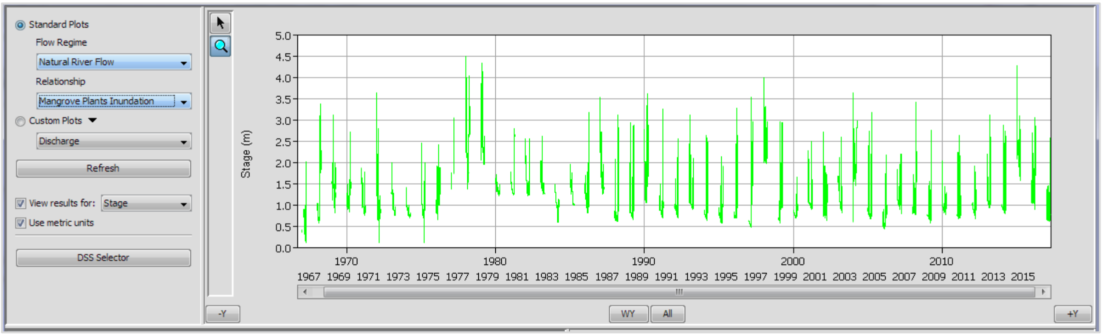


Figure 4.12: Daily Flow Duration Curve for the Umba River at 3KG01 Gauging Station

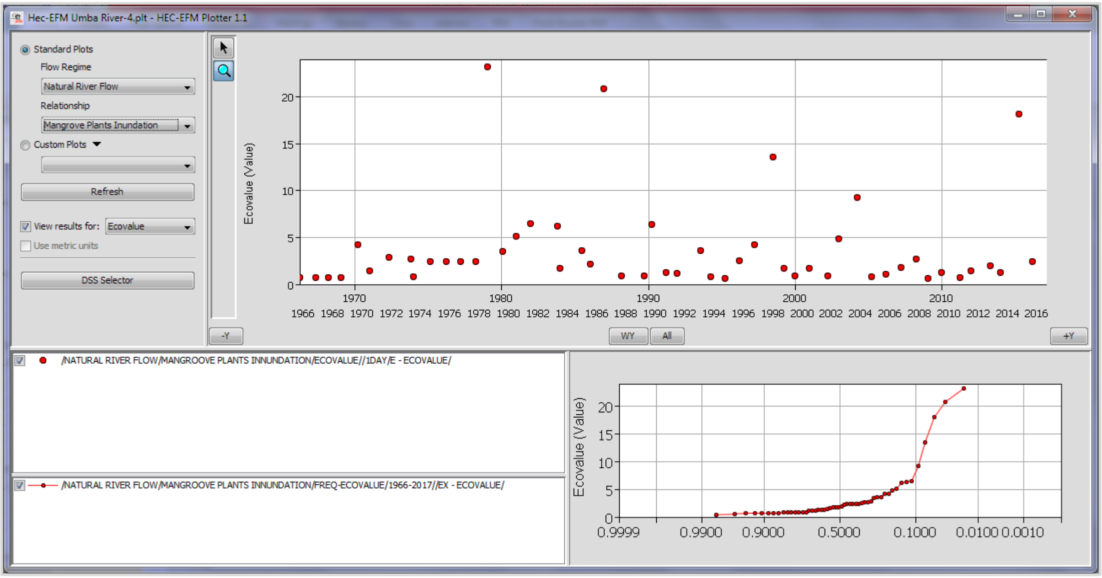
For each ecosystem group, the model extracted the daily river flow data of the specified season from each year to be used for seasonal and statistical analysis. Figure 4.13 shows the daily water levels (stages) extracted from the selected season of each year for mangrove plants inundation. The left section of the figure shows the selection preferences for the flow regime, relationship (ecosystem group), and the result to be displayed. The right part of the figure presents the time series of the selected water levels in each year of the available natural flow regime.



● Standard Plots
Flow Regime: Natural River Flow
Relationship: Mangrove Plants Inundation
○ Custom Plots
Discharge
☑ View results for: Stage
☑ Use metric units

Figure 4.13: Daily Water Levels extracted from the specified Season of each year for Mangrove Plants Inundation

Seasonal results were computed with the help of HEC-EFM plotter for each relationship to show and compare how the ecosystem groups perform in each year. Figure 4.14 shows the seasonal results of mangrove plants inundation and the distribution of the ecovalues with their exceedance probabilities. Ecovalues are measures of how well flow regimes meet the needs of relationships and they are computed from the selected flow data based on the hypothesis tracking (Hickey et al., 2015; USACE, 2017). The graph at the lower right section of Figure 4.14 shows the distribution of the computed ecovalues plotted against their exceedance probabilities. The performance of the mangrove plants is similar for many of the years with the exception of few high performances.



Hec-EFM Umba River-4.plt - HEC-EFM Plotter 1.1

● Standard Plots
Flow Regime: Natural River Flow
Relationship: Mangrove Plants Inundation
○ Custom Plots
☑ View results for: Ecovalue
☐ Use metric units

☑ ● /NATURAL RIVER FLOW/MANGROOVE PLANTS INNUNDATION/ECOVALUE//1DAY/E - ECOVALUE/

☑ /NATURAL RIVER FLOW/MANGROOVE PLANTS INNUNDATION/FREQ-ECOVALUE/1966-2017//EX - ECOVALUE/

Figure 4.14: Seasonal Results for Mangrove Plants Inundation and Distribution of Ecovalues with their Exceedance Probabilities

By analysing the historical flow regime in the specified seasons, the statistical results were then computed as stages, flows, and percentage exceedance (Table 4.4). These are single performance measures that meet the statistical criteria specified for each relationship of the ecosystem groups. From the flow regime, composed of daily time series of water levels (stages) and discharges, the valid years with no missing records in the specified seasons were selected by the model.

Table 4.4: Summary of the Statistical Results from HEC-EFM

S. No.	*Ecosystem Group*	*Season*	*Valid years*	*Stage (m)*	*Flow (m^3/s)*	*Daily exceedance probability (%)*
1	Aquatic Animals	Oct - May	41	1.3	3.0	31
2	Mangrove Plants Recruitment	Nov - Jan	44	1.7	6.6	18
3	Mangrove Plants Inundation	Jan - Mar	47	1.5	4.6	24
4	Riparian Trees Recruitment	Oct - Dec	45	1.6	5.5	21
5	Riparian Trees Inundation	Jan - Mar	47	1.6	5.5	21
6	Macroinvertebrates	Sep - Aug	41	3.3	48.3	1
7	Floodplain Wetlands	Sep - Apr	50	1.1	1.9	42

For the Aquatic animals, a river flow of 3 m^3/s with a water level of 1.3 m, at the gauging station, is calculated from the 41 selected flow years to satisfy the spawning of the aquatic animals in the months of October to May. To provide the recruitment (November to January) and inundation (January to March) of mangrove plants, the respective flows of more than 6.6 m^3/s and 4.6 m^3/s should flow. Similarly discharges higher than 5.5 m^3/s, flowing from October up to March, can satisfy the recruitment and inundation of the riparian trees. To initiate the natural conditions of the river and encourage the macroinvertebrates, the river needs a flood flow with stage more than 3.3 m at any time of a year. A river flow of more than 1.9 m^3/s flowing between September and April can support successful exchange of water between the river and the wetlands and help to maintain wetland health. The last column of Table 4.4 presents the percentage of the daily exceedance probability for the stage and flow values compared with the historical flow regime of the river.

The study focused on evaluating the performance of the existing ecologic conditions including aquatic, riparian, wetland, and estuarine ecosystems. The current state of the Umba riverine ecosystems has been characterized with reference to their connection with the river flow. The statistical relationships between the historical natural flow regime and different ecosystem groups of the Umba River were evaluated using HEC-EFM model. The above results are helpful for identifying the important flow dynamics that satisfies the timing of species life stages and requisite conditions for their success. The findings can be considered as baseline information and when developments are planned in the future, they will offer a way to quickly compare the management alternatives and identify the most effective project that maintains the riverine ecosystem.

4.5. Hydraulic Simulation and Assessment of Flow characteristics

A hydraulic model was setup using HEC-RAS to simulate the streamflow and investigate the hydraulic flow characteristics for the lower 45 km reach of the Umba River. The river system comprises of a single reach with a meandering profile and mild slope. The elevation ranges from sea level at the Indian Ocean to about 70 m above sea level where the river crosses the Kenya-Tanzania border. The river system schematic, as displayed in Figure 4.15, was prepared with 45 cross-sections spaced 1 km apart. Each cross-section in the model is identified by its River Station (RS) label.

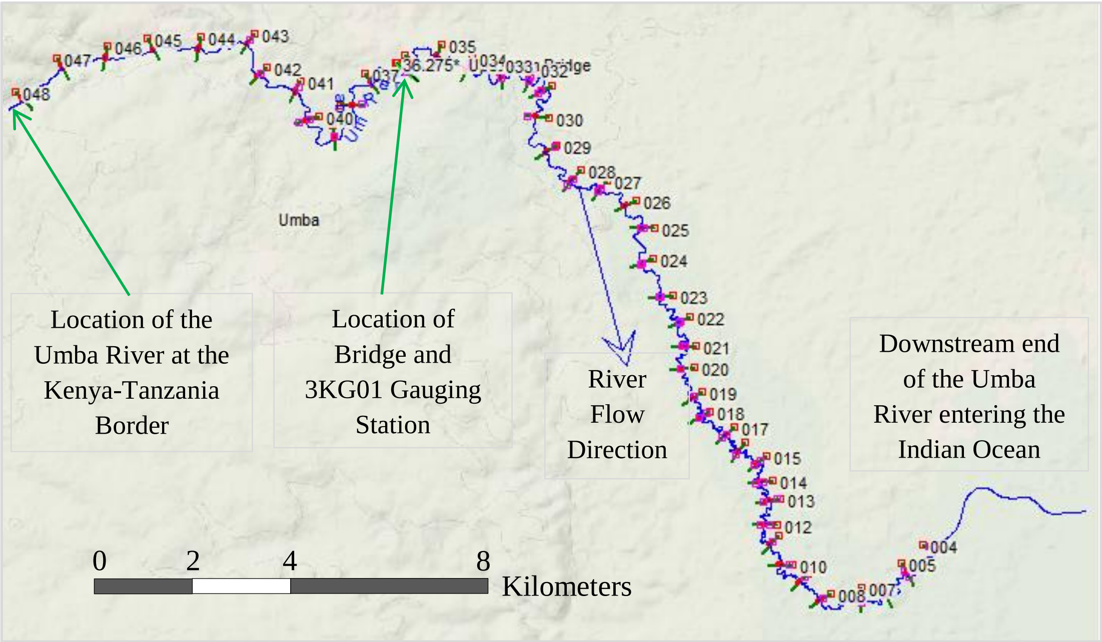


Figure 4.15: River Profile for the Lower 45 km Reach of the Umba River

Figure 4.16 shows the cross-sectional profile of the river channel at the location of the 3KG01 gauging station. Similar profiles were prepared throughout the river reach starting from the Tanzania-Kenya border up to the Indian Ocean. The width of the river channel sections were found to range from 30 m to 80 m.

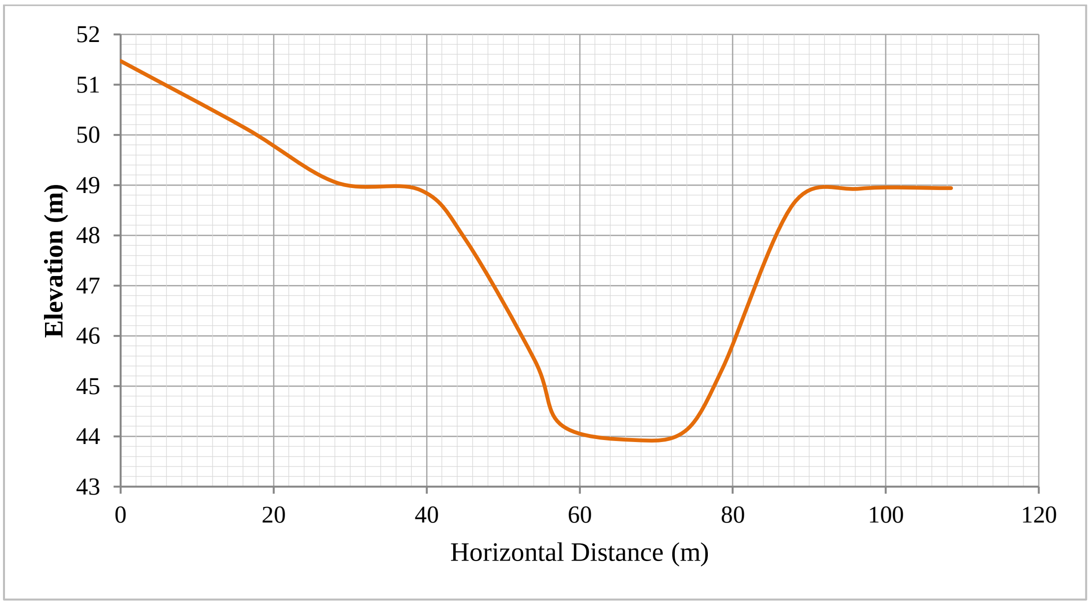


Figure 4.16: Channel Cross-sectional Profile at 3KG01 Gauging Station

According to the solution of the one-dimensional energy equation, the water surface elevation and the total energy head are considered constant at each cross-section. Energy losses between adjacent cross-sections are evaluated by friction derived from Manning's equation and contraction/expansion of the channel. The momentum equation is utilized in situations where the water surface profile is rapidly varied. These situations include mixed flow regime calculations, hydraulic jumps, hydraulics of bridges, and evaluating profiles at river confluences (stream junctions). The effects of various obstructions are also considered in the computations.

The transition energy losses between two adjacent cross-sections were considered using the gradual contraction and expansion coefficients of 0.1 and 0.3. Similarly values of 0.3 and 0.5 were used at the bridge cross-sections (USACE, 2016a). 40 Flow Profiles (FP) covering the full range of the flows in the river were used to perform the steady flow simulations. The river reach was analyzed for mixed flow regime with a downstream boundary condition (normal depth) of S = 0.0015 m/m. This value was estimated as the average slope of the channel near the end of the river.

HEC-RAS provided various graphical and tabular outputs generated at each cross-section of the river reach. The graphical results include water surface profiles, cross-section plots, rating curves, X-Y-Z perspective plots, and inundation mapping. The observed stage-flow rating curve was used to calibrate the model. The rating curve simulated by HEC-RAS fitted well with the observed curve (Figure 4.17). Similar rating curves are generated for each cross-section of the river. Water discharges flowing along the river can be converted to their corresponding stages using the flow-stage rating curves at the cross-sections.

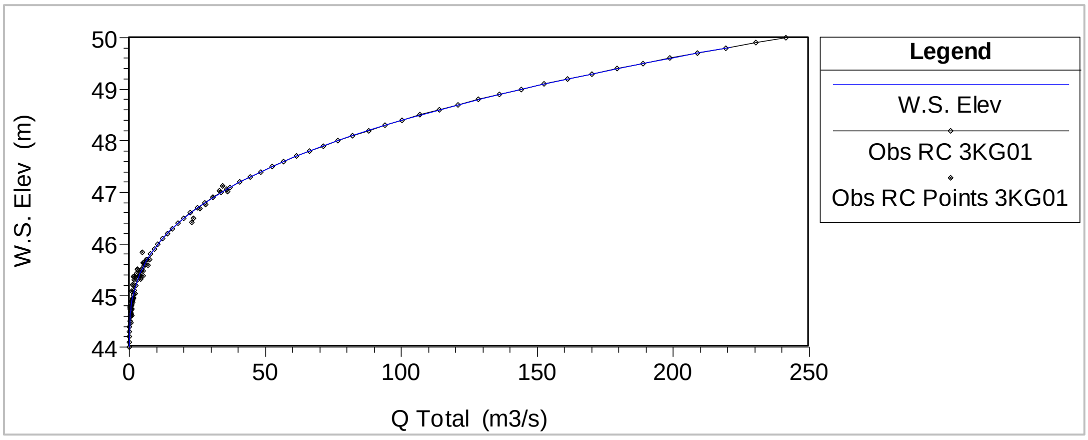


Figure 4.17: Stage-Discharge Rating Curve Comparison at 3KG01 Gauging Station

Other important results of HEC-RAS simulation are preparation of water surface and velocity profiles for each flow profile. Figure 4.18 shows the water surface profile along the river reach when a discharge of 40 m^3/s was simulated. For the same flow profile, the velocities of the water in the channel are presented in Figure 4.19. The depth and velocity varied greatly in the upper part of the reach due to significant changes in shape of the cross-section and slope of the river channel.

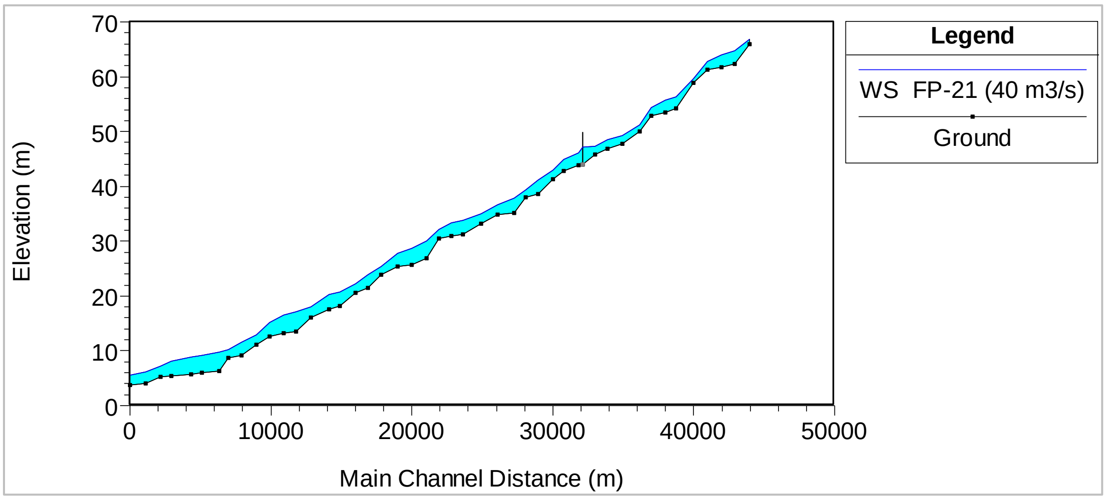


Figure 4.18: Longitudinal Water Surface Profile for the lower Umba River reach when a Discharge of 40 m^3/s was Simulated

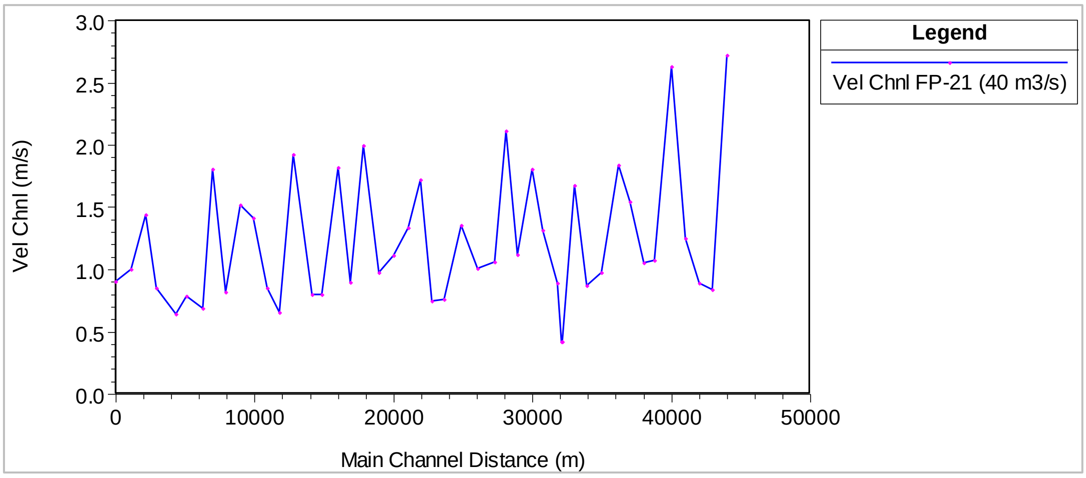


Figure 4.19: Flow Velocity Profile for the lower Umba River reach when a Discharge of 40 m^3/s was Simulated

Figure 4.20 and Figure 4.21 show the water surface profiles and velocity distributions at the bridge location and station label 16 respectively. The results are obtained for flow profile 21, when the discharge of 40 m^3/s flows in the river. The flow velocity was found higher at the central region of the channel and decreased on both sides of the cross-section.

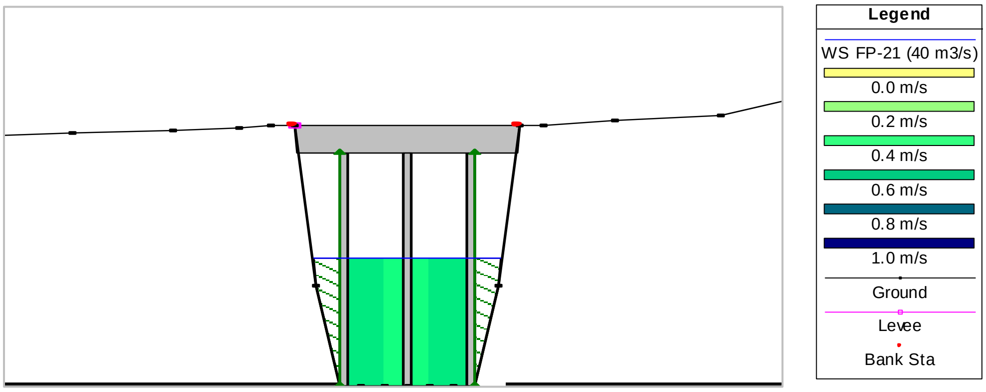


Figure 4.20: Water Surface Profile and Velocity Distribution at the Bridge Location near Lunga-Lunga

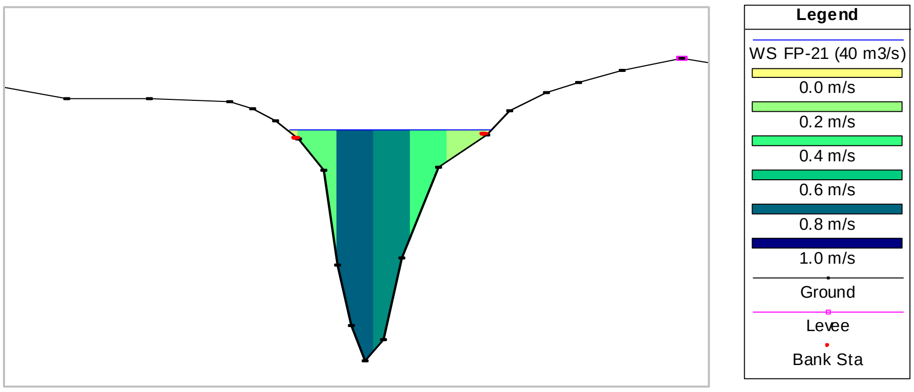
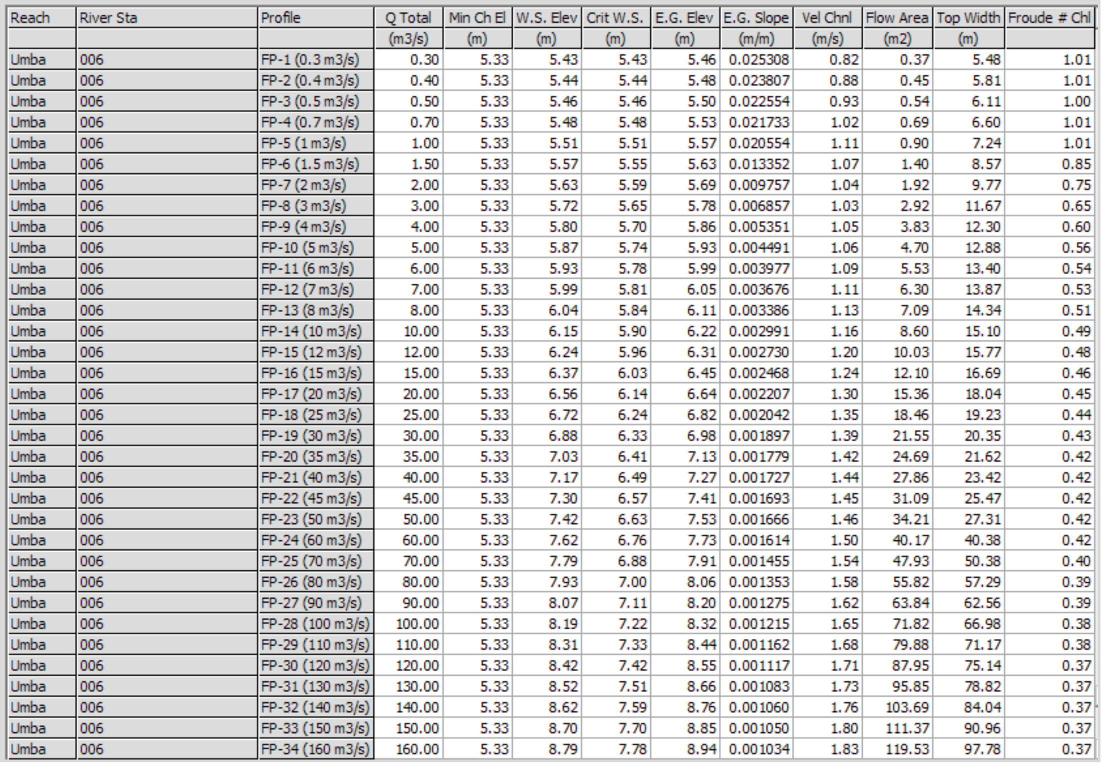


Figure 4.21: Water Surface Profile and Velocity Distribution at Cross-section 16 of Lower Umba River Reach

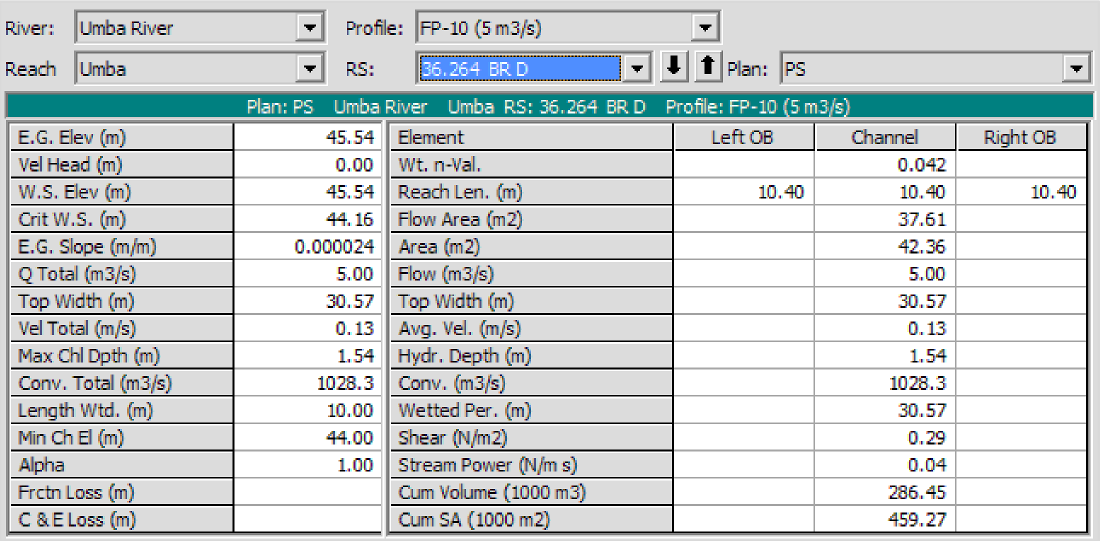
HEC-RAS has two main types of tabular outputs namely profile summary tables and detailed output tables. They allow displaying large amounts of information in a concise format which are often necessary to analyze and document the simulation results. Profile summary tables are used to display a limited number of hydraulic variables for several cross-sections while the detailed output tables present hydraulic information for a single profile at a single location. Table 4.5 shows part of the profile output table when the full range of discharge was simulated in HEC-RAS. Sample detailed output table at the downstream face of the Bridge is shown in Table 4.6 with the hydraulic results computed for a discharge of 5 m^3/s. The results of any cross-section and flow profile can be displayed in the table by selecting the appropriate profile and river station label.

Table 4.5: Sample Profile Summary Table output from HEC-RAS Model at River Station 6 of the Umba River Reach



Reach	River Sta	Profile	Q Total	Min Ch El	W.S. Elev	Crit W.S.	E.G. Elev	E.G. Slope	Vel Chnl	Flow Area	Top Width	Froude # Chl
			(m3/s)	(m)	(m)	(m)	(m)	(m/m)	(m/s)	(m2)	(m)	
Umba	006	FP-1 (0.3 m3/s)	0.30	5.33	5.43	5.43	5.46	0.025308	0.82	0.37	5.48	1.01
Umba	006	FP-2 (0.4 m3/s)	0.40	5.33	5.44	5.44	5.48	0.023807	0.88	0.45	5.81	1.01
Umba	006	FP-3 (0.5 m3/s)	0.50	5.33	5.46	5.46	5.50	0.022554	0.93	0.54	6.11	1.00
Umba	006	FP-4 (0.7 m3/s)	0.70	5.33	5.48	5.48	5.53	0.021733	1.02	0.69	6.60	1.01
Umba	006	FP-5 (1 m3/s)	1.00	5.33	5.51	5.51	5.57	0.020554	1.11	0.90	7.24	1.01
Umba	006	FP-6 (1.5 m3/s)	1.50	5.33	5.57	5.55	5.63	0.013352	1.07	1.40	8.57	0.85
Umba	006	FP-7 (2 m3/s)	2.00	5.33	5.63	5.59	5.69	0.009757	1.04	1.92	9.77	0.75
Umba	006	FP-8 (3 m3/s)	3.00	5.33	5.72	5.65	5.78	0.006857	1.03	2.92	11.67	0.65
Umba	006	FP-9 (4 m3/s)	4.00	5.33	5.80	5.70	5.86	0.005351	1.05	3.83	12.30	0.60
Umba	006	FP-10 (5 m3/s)	5.00	5.33	5.87	5.74	5.93	0.004491	1.06	4.70	12.88	0.56
Umba	006	FP-11 (6 m3/s)	6.00	5.33	5.93	5.78	5.99	0.003977	1.09	5.53	13.40	0.54
Umba	006	FP-12 (7 m3/s)	7.00	5.33	5.99	5.81	6.05	0.003676	1.11	6.30	13.87	0.53
Umba	006	FP-13 (8 m3/s)	8.00	5.33	6.04	5.84	6.11	0.003386	1.13	7.09	14.34	0.51
Umba	006	FP-14 (10 m3/s)	10.00	5.33	6.15	5.90	6.22	0.002991	1.16	8.60	15.10	0.49
Umba	006	FP-15 (12 m3/s)	12.00	5.33	6.24	5.96	6.31	0.002730	1.20	10.03	15.77	0.48
Umba	006	FP-16 (15 m3/s)	15.00	5.33	6.37	6.03	6.45	0.002468	1.24	12.10	16.69	0.46
Umba	006	FP-17 (20 m3/s)	20.00	5.33	6.56	6.14	6.64	0.002207	1.30	15.36	18.04	0.45
Umba	006	FP-18 (25 m3/s)	25.00	5.33	6.72	6.24	6.82	0.002042	1.35	18.46	19.23	0.44
Umba	006	FP-19 (30 m3/s)	30.00	5.33	6.88	6.33	6.98	0.001897	1.39	21.55	20.35	0.43
Umba	006	FP-20 (35 m3/s)	35.00	5.33	7.03	6.41	7.13	0.001779	1.42	24.69	21.62	0.42
Umba	006	FP-21 (40 m3/s)	40.00	5.33	7.17	6.49	7.27	0.001727	1.44	27.86	23.42	0.42
Umba	006	FP-22 (45 m3/s)	45.00	5.33	7.30	6.57	7.41	0.001693	1.45	31.09	25.47	0.42
Umba	006	FP-23 (50 m3/s)	50.00	5.33	7.42	6.63	7.53	0.001666	1.46	34.21	27.31	0.42
Umba	006	FP-24 (60 m3/s)	60.00	5.33	7.62	6.76	7.73	0.001614	1.50	40.17	40.38	0.42
Umba	006	FP-25 (70 m3/s)	70.00	5.33	7.79	6.88	7.91	0.001455	1.54	47.93	50.38	0.40
Umba	006	FP-26 (80 m3/s)	80.00	5.33	7.93	7.00	8.06	0.001353	1.58	55.82	57.29	0.39
Umba	006	FP-27 (90 m3/s)	90.00	5.33	8.07	7.11	8.20	0.001275	1.62	63.84	62.56	0.39
Umba	006	FP-28 (100 m3/s)	100.00	5.33	8.19	7.22	8.32	0.001215	1.65	71.82	66.98	0.38
Umba	006	FP-29 (110 m3/s)	110.00	5.33	8.31	7.33	8.44	0.001162	1.68	79.88	71.17	0.38
Umba	006	FP-30 (120 m3/s)	120.00	5.33	8.42	7.42	8.55	0.001117	1.71	87.95	75.14	0.37
Umba	006	FP-31 (130 m3/s)	130.00	5.33	8.52	7.51	8.66	0.001083	1.73	95.85	78.82	0.37
Umba	006	FP-32 (140 m3/s)	140.00	5.33	8.62	7.59	8.76	0.001060	1.76	103.69	84.04	0.37
Umba	006	FP-33 (150 m3/s)	150.00	5.33	8.70	7.70	8.85	0.001050	1.80	111.37	90.96	0.37
Umba	006	FP-34 (160 m3/s)	160.00	5.33	8.79	7.78	8.94	0.001034	1.83	119.53	97.78	0.37

Table 4.6: Sample Detailed Output Table at the Downstream Cross-section of the Bridge for a Discharge of 5 m^3/s



River: Umba River

Profile: FP-10 (5 m3/s)

Reach Umba

RS: 36.264 BR D

Plan: PS

Plan: PS Umba River Umba RS: 36.264 BR D Profile: FP-10 (5 m3/s)

E.G. Elev (m)	45.54	Element	Left OB	Channel	Right OB
Vel Head (m)	0.00	Wt. n-Val.		0.042	
W.S. Elev (m)	45.54	Reach Len. (m)	10.40	10.40	10.40
Crit W.S. (m)	44.16	Flow Area (m2)		37.61	
E.G. Slope (m/m)	0.000024	Area (m2)		42.36	
Q Total (m3/s)	5.00	Flow (m3/s)		5.00	
Top Width (m)	30.57	Top Width (m)		30.57	
Vel Total (m/s)	0.13	Avg. Vel. (m/s)		0.13	
Max Chl Dpth (m)	1.54	Hydr. Depth (m)		1.54	
Conv. Total (m3/s)	1028.3	Conv. (m3/s)		1028.3	
Length Wtd. (m)	10.00	Wetted Per. (m)		30.57	
Min Ch El (m)	44.00	Shear (N/m2)		0.29	
Alpha	1.00	Stream Power (N/m s)		0.04	
Frctn Loss (m)		Cum Volume (1000 m3)		286.45	
C & E Loss (m)		Cum SA (1000 m2)		459.27	

Table 4.7 presents a summary of the hydraulic modelling results computed by HEC-RAS when the entire ranges of discharges were simulated. When a flow of 0.4 m^3/s (Q-95) was simulated, the average water depth was found 0.28 m with a minimum of 0.1 m and maximum of 0.66 m. The average stream velocity in the reach was 0.37 m/s. As the flow increased to 0.50 m^3/s (Q-90), the average flow depth and stream velocity increased to 0.30 m and 0.40 m/s respectively. For a flow of 2 m^3/s, the water depth ranged from 0.18 m to 1.13 m with an average value of 0.56 m. The average stream velocity was found 0.58 m/s with a minimum of 0.06 m/s at the bridge location and a maximum of 1.47 m/s at section 17. As the flow increased to 5 m^3/s, the average flow depth and stream velocity increased to 0.84 m and 0.75 m/s respectively.

When the river flow reached 7 m^3/s, the average water depth was found 0.97 m and the average velocity reached 0.83 m/s. With increase of the discharge to 12 m^3/s, the flow reaches the flood plains on some cross-sections. A flow of 50 m^3/s inundated the flood plains for most of the cross-sections and results a water depth in the range of 1.00 m to 3.80 m with an average value of 2.40 m. The stream velocity during this flow ranges from 0.50 m/s to 2.90 m/s with an average value of 1.32 m/s. The river flow of 120 m^3/s was found to overflow from the flood plains and covering large farm areas near the river.

Table 4.7: Summary of the Water Depth and Flow Velocity Computed by HEC-RAS for the full range of Discharges

Flow Profile	Q (m^3/s)	Min Depth (m)	Max Depth (m)	Ave Depth (m)	Min Vel (m/s)	Max Vel (m/s)	Ave Vel (m/s)
1	0.3	0.06	0.60	0.25	0.02	1.12	0.36
2	0.4	0.08	0.66	0.28	0.02	1.18	0.37
3	0.5	0.09	0.71	0.30	0.02	1.24	0.40
4	0.7	0.11	0.79	0.35	0.03	1.33	0.44
5	1	0.13	0.89	0.41	0.04	1.22	0.48
6	1.5	0.15	1.02	0.49	0.05	1.37	0.54
7	2	0.18	1.13	0.56	0.06	1.47	0.58
8	3	0.22	1.29	0.66	0.08	1.62	0.65
9	4	0.25	1.43	0.76	0.09	1.74	0.71
10	5	0.28	1.54	0.84	0.11	1.85	0.75
11	6	0.31	1.64	0.91	0.12	1.93	0.79
12	7	0.33	1.73	0.97	0.13	1.99	0.83
13	8	0.35	1.82	1.03	0.15	2.06	0.86
14	10	0.39	1.96	1.14	0.17	2.17	0.92
15	12	0.43	2.09	1.24	0.19	2.25	0.96
16	15	0.49	2.27	1.37	0.22	2.37	1.02
17	20	0.57	2.56	1.57	0.27	2.37	1.09
18	25	0.65	2.80	1.74	0.31	2.45	1.14
19	30	0.72	3.03	1.91	0.35	2.49	1.16
20	35	0.78	3.39	2.07	0.38	2.61	1.18
21	40	0.85	3.57	2.20	0.42	2.72	1.21
22	45	0.91	3.69	2.29	0.45	2.82	1.29
23	50	0.96	3.79	2.39	0.48	2.90	1.32
24	60	1.07	3.98	2.55	0.54	3.30	1.44
25	70	1.18	4.17	2.71	0.60	3.44	1.51
26	80	1.27	4.32	2.82	0.65	3.55	1.65
27	90	1.36	4.45	2.97	0.34	3.72	1.59
28	100	1.45	4.56	3.11	0.36	3.79	1.60
29	110	1.54	4.70	3.19	0.38	3.87	1.70
30	120	1.63	4.84	3.32	0.37	3.93	1.70
31	130	1.74	5.00	3.38	0.36	4.14	1.76
32	140	1.60	5.13	3.43	0.35	4.13	1.81
33	150	1.94	5.22	3.59	0.35	3.81	1.70
34	160	2.04	5.31	3.62	0.35	3.86	1.77
35	170	2.14	5.39	3.72	0.34	3.90	1.75
36	180	2.27	5.47	3.79	0.34	3.94	1.78
37	190	2.36	5.54	3.86	0.34	3.98	1.80
38	200	2.41	5.65	3.92	0.34	4.02	1.83
39	210	2.45	5.75	3.98	0.34	4.06	1.85
40	221	2.51	5.97	4.04	0.34	3.99	1.81

The results of the hydraulic model simulations comprise a series of relationships between streamflow and other flow parameters that help for performing environmental flow assessments. These parameters include water depth, flow velocity, wetted perimeter, flow area, and water surface width (USACE, 2016a). Fresh water flows are necessary for aquatic species, riparian biodiversity, wetlands, and estuaries. River water level controls the water depth that enables spawning of aquatic animals and the water table which dictates water availability to riparian plants. Reduction of water flow affects aquatic life by reducing dissolved oxygen and supply of nutrients (Dickens, 2011).

Environmental flows are not just about the provision of low flow levels. Some of the most important functions of environmental flows require periodic high flows. Maintaining only low flows without consideration of the wider range and timing of the flows is not sufficient for the health of the river ecosystems and their services. Understanding the environmental flows of a river requires recognizing the key components of the flow regime and their roles in maintaining healthy ecosystems. Provision of the environmental flow should, therefore, follow the natural flow pattern to enable the ecosystem processes function throughout the year (Risley et al., 2010; Speed et al., 2013).

Using the statistical analyses and hydraulic modelling results, analyses for the flow regime and relationships were performed. The range of water levels and discharges, their yearly exceedance probabilities and their descriptions based on ecological considerations are presented in the Table 4.8. Different flow requirements including low-flows, base flows, pulses, high flows, and flood events are identified.

Table 4.8: Flow Classification for the Lower Umba River

S. N.	*Flow Type*	*Water Level at 3KG01 (m)*	*Discharge at 3KG01 (m^3/s)*	*Daily Exceedance Probability (%)*	*Description of Flow Requirement based on Ecological Considerations*
1	Deficient Flow	< 0.3	< 0.2	> 98	Insufficient Flow, Very low Depth and Velocity.
2	Low Flow	0.3 – 0.8	0.2 – 0.7	80 - 98	Provide minimum habitat for species, Survival of organisms, Improve stagnant water quality, Supply dissolved oxygen, and Maintain flow connectivity.
3	Base Flow	0.8 – 1.4	0.7 – 4.0	26 - 80	Maintaining habitat in channel, Restore organic matter levels, Control water chemistry, Provide sufficient velocities, Prevent saline intrusion, and Maintaining water table levels.
4	Pulse Flow	1.4 – 2.5	4.0 – 20	5 - 26	Inundating floodplains and Mangroves, Recruitment of riparian vegetation, River habitat connectivity, Trigger spawning and migration, Provide foraging, breeding and rearing, Enhance growth and reproduction, Improving water quality, Nutrient availability, and Maintaining appropriate salinity levels.
5	High Flow	2.5 – 3.5	20 – 50	0.5 – 5.0	Shaping the river channel and streambed, Inundate wetlands, Recharge ground water table, Promote biomass increase, and Prevent invasive species.
6	Flood Flow	3.5 – 4.7	50 - 120	0.02 – 0.50	Maintain channel forms, Flushing accumulated organic matter, Sediment transport, and Regulate species composition and diversity.
7	Overflood	> 4.7	> 120	< 0.02	Overflow from the flood plains and damage to farm areas

When discharges of less than 0.20 m^3/s flow in the Umba River, the depth of the water reaches below 0.10 m on many of the river locations. This may lead to discontinuity in the flowing water and hence considered as insufficient flow. The low-flow (0.20 m^3/s to 0.70 m^3/s) is important to provide minimum habitat for species, prevent invasive species, improve stagnant water quality, maintain the flow connectivity, and to supply dissolved oxygen for survival of organisms in the river. The base flows (0.7 m^3/s to 4.0 m^3/s) are helpful for maintaining wet channels, restoring organic matters, maintaining water table levels, to provide sufficient velocities, and prevent saline intrusions. Pulse flows (4 m^3/s to 20 m^3/s) are important for inundating floodplains and mangroves, nutrient availability, trigger spawning and migration, provide breeding and rearing, enhance growth and reproduction, improving water quality, and maintaining appropriate salinity levels. High flows (20 m^3/s to 50 m^3/s) help in shaping the river channel, inundating wetlands, to promote biomass increase, and to purge invasive species. Floods are essential to maintain channel forms, to flush out accumulated organic matter, sediment transport, and regulate species composition and diversity.

The one day flow duration curve is classified based on these flow groups as shown in Figure 4.22. These flows are necessary in different months of a year to maintain species and the conditions for life in the flowing water of the Umba River. Discharge requirements to sustain the geomorphological functions of the Umba River reflect the seasonal variability in different months. Figure 4.23 shows the monthly flow characteristics that the aquatic and riparian biotas of the river have been adapted. The monthly standard deviation illustrates the flow variability in each month. The parallel graph of the mean monthly flow and monthly standard deviation indicated the flow variability increased with flow value.

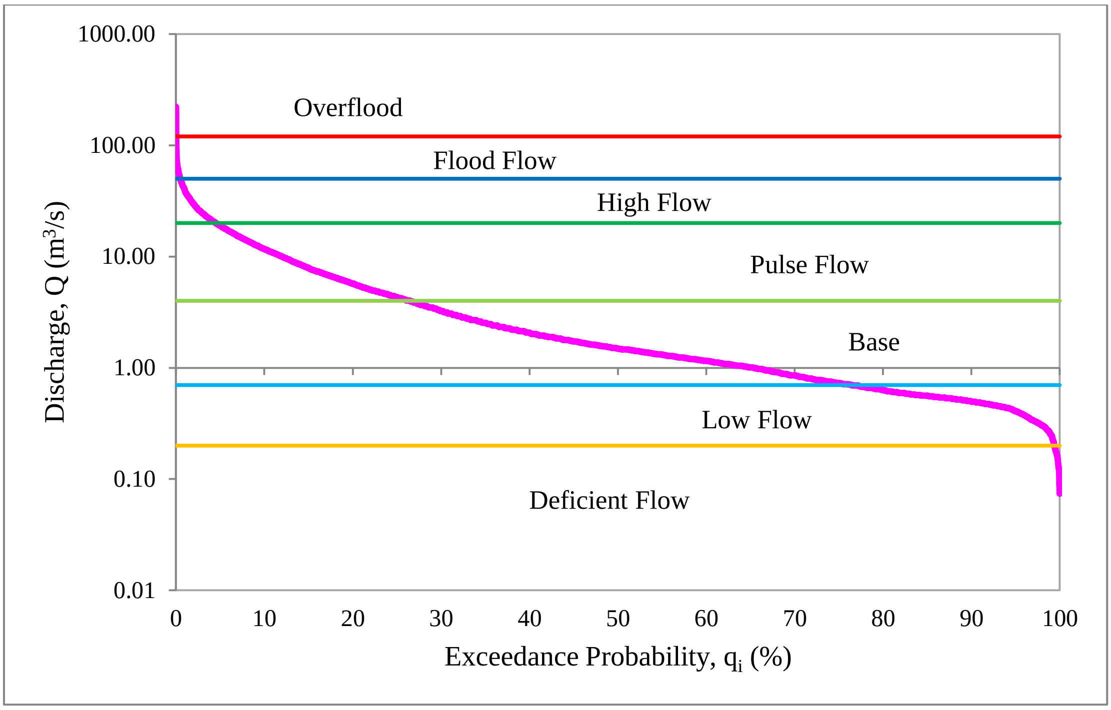


Figure 4.22: Flow Duration Curve Classification for the Lower Umba River

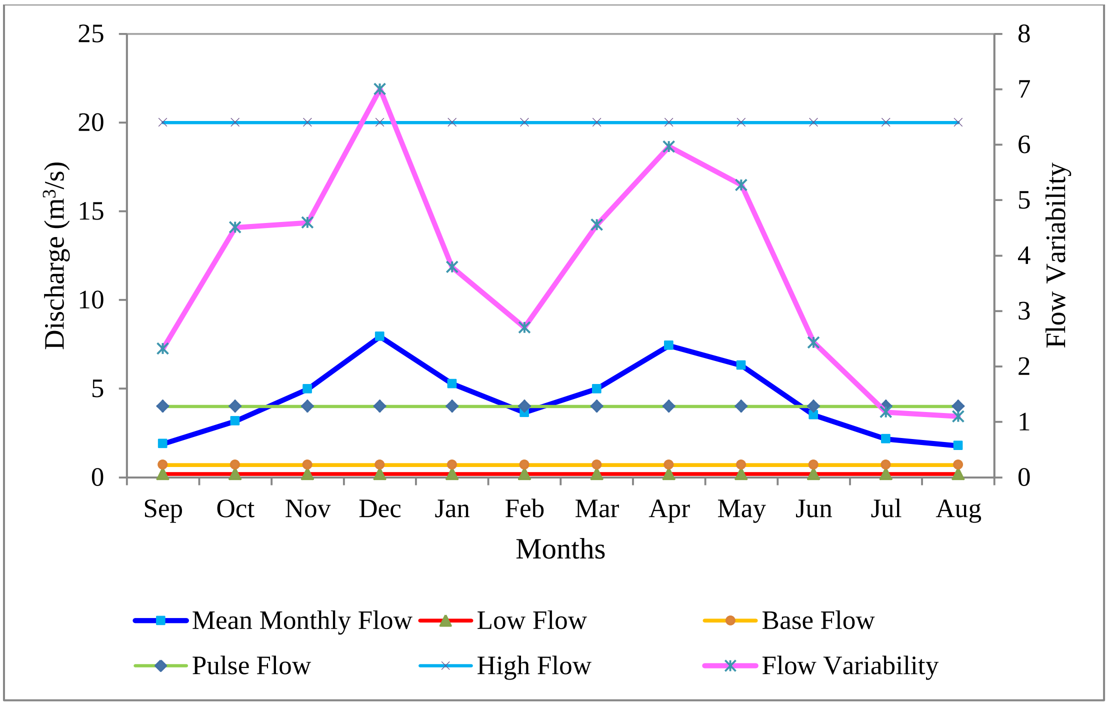


Figure 4.23: Monthly Flow Characteristics for the Lower Umba River Reach

The natural hydrologic variability and dynamic character of the Umba River has an ecological importance. The water needs that meet the seasonality and stage recession criteria required by the species of interest vary at different times of the year. The species that inhabit the channel and adjacent riparian zones are adapted to the seasonal changes from low to high flows. They depend on the characteristics of the streamflow regime, magnitude and timing, for their success (Risley et al., 2010). Therefore, water for the ecosystems and recommendations for environmental flows should follow this natural flow seasonality during management and allocation plans of the river.

Both the Kenyan and Tanzanian national water policies and laws recognize for the provision of reserve flows, minimum water levels left in the river in order to sustain basic human needs and aquatic ecosystems (FIU-GLOWS, 2016; GLOWS-FIU, 2012). However, few studies have been done on assessment of variable environmental flows before implementation of projects. EFA study performed on the Kibos River to assess the impact of a proposed water diversion on the river revealed an environmental change up on implementation of the project (Wakitolie, 2013).

The Global Water for Sustainability Program (GLOWS) in collaboration with Florida International University (FIU) has developed EFA for the Mara and Wami River Basins (GLOWS-FIU, 2012, 2014). Flow recommendations were made on a month by month basis that can be presented as a set of flow targets for water resource managers (FIU-GLOWS, 2016). The results of those studies along with this research support the need for comprehensive plans and frame works to secure the in stream flows needed to maintain the bio-diversity of fresh water life and to sustain their ecological functions.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

From this research it can easily be concluded that:

i. The HEC-HMS model performed well to simulate continuous time series of daily streamflow for the last 30 years. Although there is over prediction of the simulated flow compared with the observed flow, the results are satisfactory to infill the missing records and to extend the streamflow data of the Umba River.

ii. Seasonal and statistical results are computed for aquatic animals, mangrove plants, riparian trees, macroinvertebrates, and floodplain wetlands by using HEC-EFM model. The results can be considered as baseline information for comparing project alternatives that best meet developmental needs for water without significantly compromising environmental quality of the Umba River.

iii. Results from the HEC-RAS model were successfully used to investigate the relationships between the hydraulic flow characteristics and the natural environmental flows. Different flow types including low flows (0.20 m^3/s to 0.70 m^3/s), base flows (0.7 m^3/s to 4.0 m^3/s), pulses (4 m^3/s to 20 m^3/s), high flows (20 m^3/s to 50 m^3/s), and flood events (50 m^3/s to 120 m^3/s) need to flow in different months of the year to preserve the riverine ecosystems and maintain their services.

The study is expected to help management decisions for efficient water resource allocation, enhancing IWRM, and maximizing ecological benefits in the river.

Moreover, it will provide hydrologic and hydraulic information for cross-border collaboration for integrated management of Shared Trans-Boundary Ecosystems (STEs) in the basin. However, environmental flow assessment is a continuous process which needs to be updated and improved by using higher resolution data and incorporating future data monitoring plans.

5.2. Recommendations

To ensure the provision of sustainable water flows in the river the following recommendations are made:

i. Continuous collection of data on hydrology, hydraulics, and ecology;

ii. Development of a framework of joint management of this transboundary river and sharing of hydrological data between Kenya and Tanzania; and

iii. Consideration of environmental flows at the planning stage of future water resources development projects in the river.

5.3. Future Research

Additional research is required in the following areas:

i. Study and inventory of the biodiversity to increase the scientific understanding of the riverine ecosystems at species level;

ii. Economic valuation of the ecosystem services in the Umba river; and

iii. Modelling the estuary to relate salinity with freshwater inflows, sediment distribution, and water quality.

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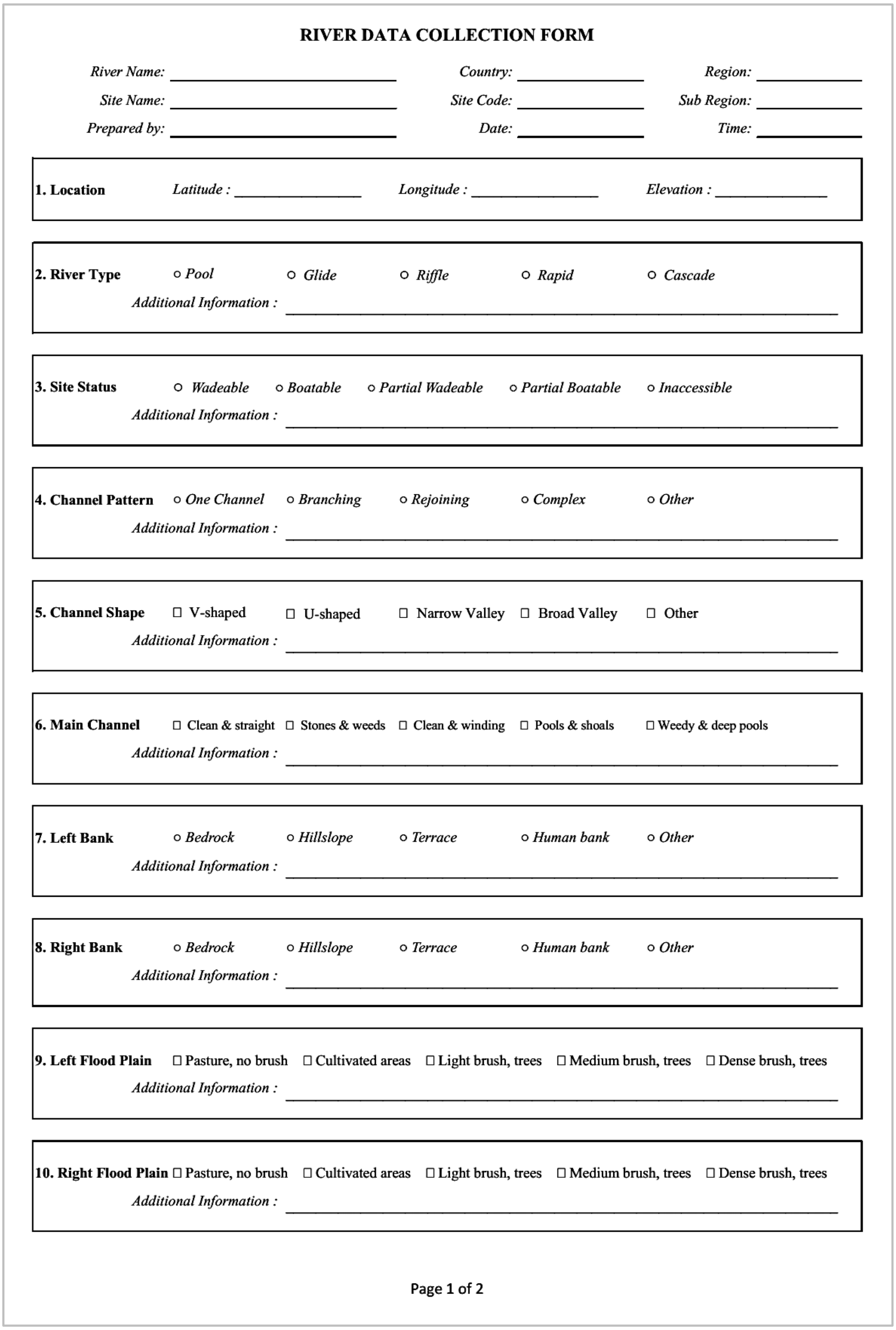
APPENDICES

Appendix A: River Data Collection Form used during River Assessment



RIVER DATA COLLECTION FORM

River Name: ____________________ *Country:* ____________ *Region:* __________

Site Name: ____________________ *Site Code:* ____________ *Sub Region:* __________

Prepared by: ____________________ *Date:* ____________ *Time:* __________

1. Location *Latitude :* ____________ *Longitude :* ____________ *Elevation :* ____________

2. River Type ○ *Pool* ○ *Glide* ○ *Riffle* ○ *Rapid* ○ *Cascade*

Additional Information : ____

3. Site Status ○ *Wadeable* ○ *Boatable* ○ *Partial Wadeable* ○ *Partial Boatable* ○ *Inaccessible*

Additional Information : ____

4. Channel Pattern ○ *One Channel* ○ *Branching* ○ *Rejoining* ○ *Complex* ○ *Other*

Additional Information : ____

5. Channel Shape ☐ V-shaped ☐ U-shaped ☐ Narrow Valley ☐ Broad Valley ☐ Other

Additional Information : ____

6. Main Channel ☐ Clean & straight ☐ Stones & weeds ☐ Clean & winding ☐ Pools & shoals ☐ Weedy & deep pools

Additional Information : ____

7. Left Bank ○ *Bedrock* ○ *Hillslope* ○ *Terrace* ○ *Human bank* ○ *Other*

Additional Information : ____

8. Right Bank ○ *Bedrock* ○ *Hillslope* ○ *Terrace* ○ *Human bank* ○ *Other*

Additional Information : ____

9. Left Flood Plain ☐ Pasture, no brush ☐ Cultivated areas ☐ Light brush, trees ☐ Medium brush, trees ☐ Dense brush, trees

Additional Information : ____

10. Right Flood Plain ☐ Pasture, no brush ☐ Cultivated areas ☐ Light brush, trees ☐ Medium brush, trees ☐ Dense brush, trees

Additional Information : ____

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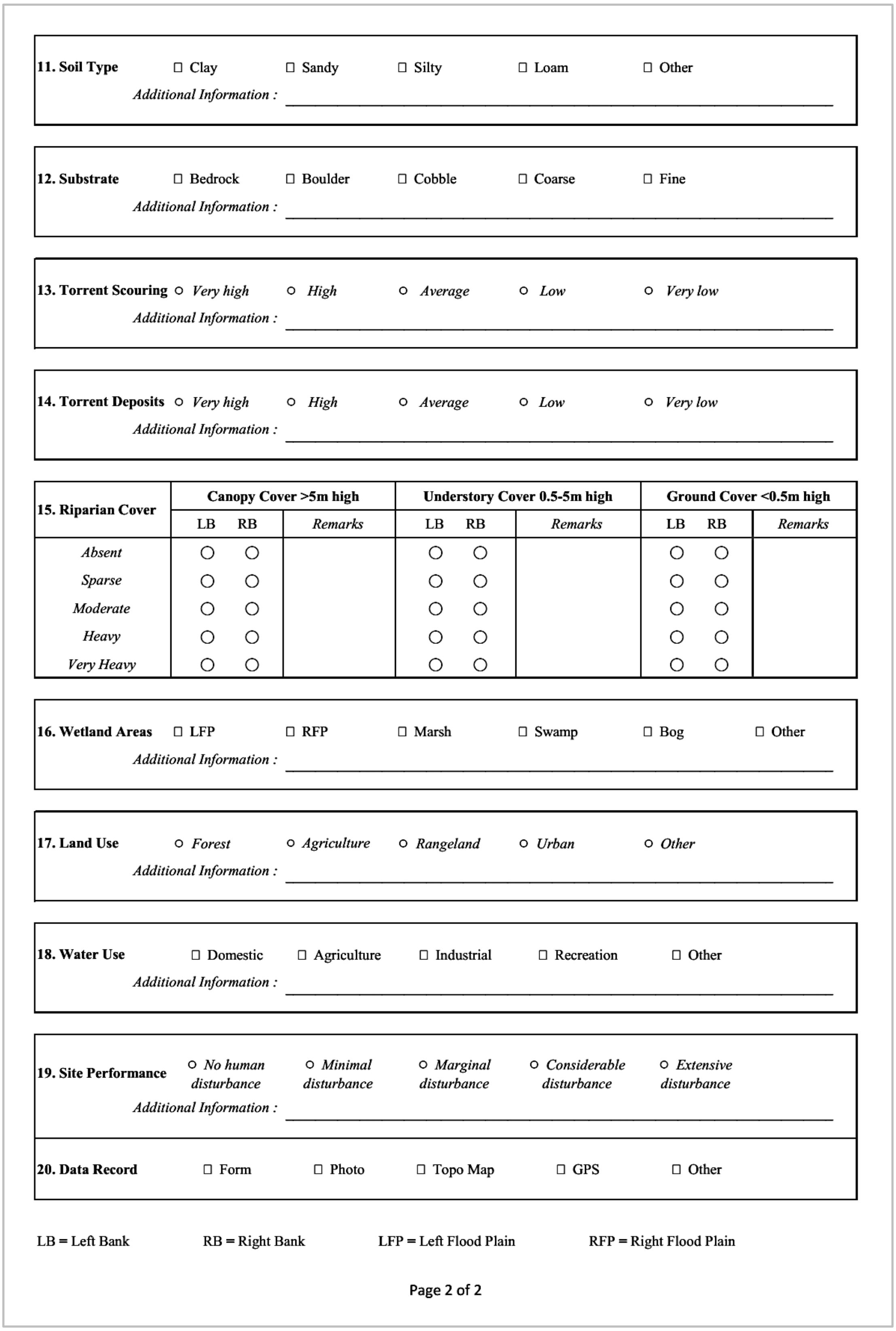

11. Soil Type ☐ Clay ☐ Sandy ☐ Silty ☐ Loam ☐ Other

Additional Information : ______

12. Substrate ☐ Bedrock ☐ Boulder ☐ Cobble ☐ Coarse ☐ Fine

Additional Information : ______

13. Torrent Scouring ○ *Very high* ○ *High* ○ *Average* ○ *Low* ○ *Very low*

Additional Information : ______

14. Torrent Deposits ○ *Very high* ○ *High* ○ *Average* ○ *Low* ○ *Very low*

Additional Information : ______

15. Riparian Cover	**Canopy Cover >5m high**			**Understory Cover 0.5-5m high**			**Ground Cover <0.5m high**		
	LB	RB	*Remarks*	LB	RB	*Remarks*	LB	RB	*Remarks*
Absent	○	○		○	○		○	○	
Sparse	○	○		○	○		○	○	
Moderate	○	○		○	○		○	○	
Heavy	○	○		○	○		○	○	
Very Heavy	○	○		○	○		○	○	

16. Wetland Areas ☐ LFP ☐ RFP ☐ Marsh ☐ Swamp ☐ Bog ☐ Other

Additional Information : ______

17. Land Use ○ *Forest* ○ *Agriculture* ○ *Rangeland* ○ *Urban* ○ *Other*

Additional Information : ______

18. Water Use ☐ Domestic ☐ Agriculture ☐ Industrial ☐ Recreation ☐ Other

Additional Information : ______

19. Site Performance ○ *No human disturbance* ○ *Minimal disturbance* ○ *Marginal disturbance* ○ *Considerable disturbance* ○ *Extensive disturbance*

Additional Information : ______

20. Data Record ☐ Form ☐ Photo ☐ Topo Map ☐ GPS ☐ Other

LB = Left Bank RB = Right Bank LFP = Left Flood Plain RFP = Right Flood Plain

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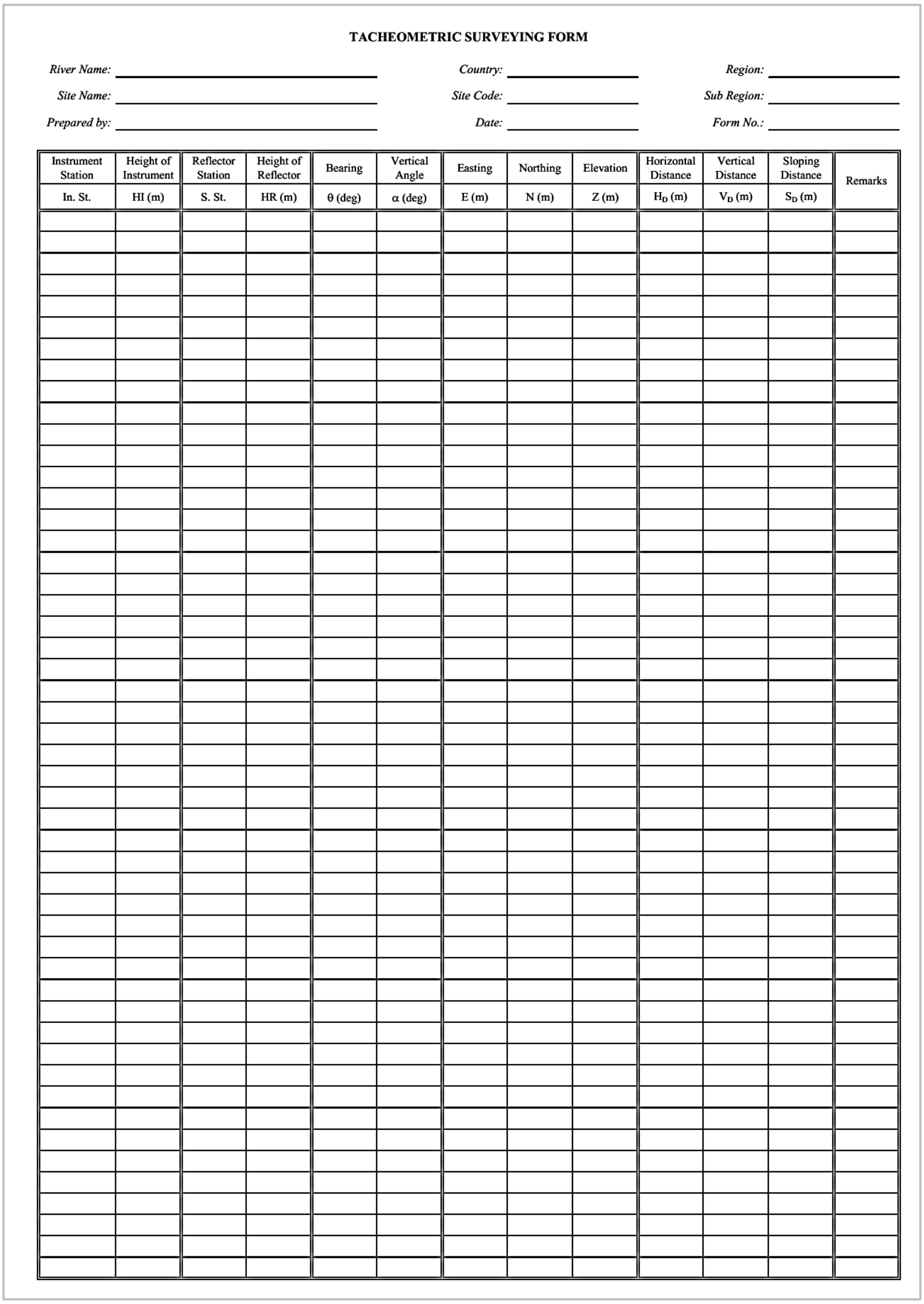
Appendix B: Tacheometric Surveying Form used during River Geometric Data collection by a Total Station



TACHEOMETRIC SURVEYING FORM

River Name: ____________________
Country: ____________
Region: ____________

Site Name: ____________________
Site Code: ____________
Sub Region: ____________

Prepared by: ____________________
Date: ____________
Form No.: ____________

Instrument Station	Height of Instrument	Reflector Station	Height of Reflector	Bearing	Vertical Angle	Easting	Northing	Elevation	Horizontal Distance	Vertical Distance	Sloping Distance	Remarks
In. St.	HI (m)	S. St.	HR (m)	θ (deg)	α (deg)	E (m)	N (m)	Z (m)	H_D (m)	V_D (m)	S_D (m)	