

# NOTE TO USERS

This reproduction is the best copy available.

**UMI**<sup>®</sup>

**DISSERTATION**

**METHODOLOGY FOR DROUGHT IMPACTS MANAGEMENT  
IN DEVELOPING COUNTRIES**

Submitted by

Zan N'Tio Traoré

Civil Engineering Department

In partial fulfillment of the requirements for the

Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Spring 2005

UMI Number: 3173095

### INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

**UMI**<sup>®</sup>

---

UMI Microform 3173095

Copyright 2005 by ProQuest Information and Learning Company.

All rights reserved. This microform edition is protected against unauthorized copying under Title 17, United States Code.


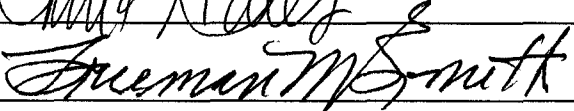
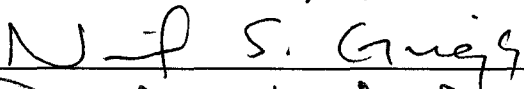

ProQuest Information and Learning Company  
300 North Zeeb Road  
P.O. Box 1346  
Ann Arbor, MI 48106-1346

**Colorado State University**

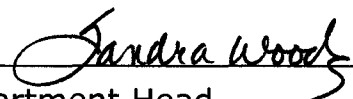
October 15, 2004

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED  
UNDER OUR SUPERVISION BY ZAN N'TIO TRAORE ENTITLED:  
**METHODOLOGY FOR DROUGHT IMPACTS  
MANAGEMENT IN DEVELOPING COUNTRIES**  
BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE  
DEGREE OF DOCTOR OF PHILOSOPHY.

**Committee on Graduate Work**

  
\_\_\_\_\_  
  
\_\_\_\_\_  
  
\_\_\_\_\_  
  
\_\_\_\_\_

Adviser

  
\_\_\_\_\_  
Department Head

## **ABSTRACT OF DISSERTATION**

### **METHODOLOGY FOR DROUGHT IMPACTS MANAGEMENT IN DEVELOPING COUNTRIES**

Droughts are occurring in many regions of the world with increased frequency and severity. Due to the recurrence and persistence of their impacts, the strategy of crisis intervention for mitigation has shown its limits. To deal not only with the immediate effects, but also with the long-term drought impacts, researchers have recommended new strategies, which are more proactive and comprehensive. Among other strategies suggested, contingency planning is one that has been adopted as a standard method of preparing for, and managing drought impacts. To this end, different planning frameworks have been proposed to drought stricken countries and places.

Capitalizing on the proposed planning frameworks, many states in the USA and other countries have defined their contingency plans for drought impacts management. However, a review of some of the existing plans evidences the need to address such critical issues as:

- ✓ The sustainability of the water resources system under consideration with respect to the demands, drought impacts and other climatic and environmental changes;
- ✓ The selection of the management options most relevant to conflicting management objectives in a developing drought;
- ✓ The definition of the timing and sequencing of the implementation of the selected management actions in order to achieve the optimal mitigation;
- ✓ The integration of the immediate objectives of drought impacts management with the strategic objectives of water resources management.

This study proposes procedures for assessing the sustainability of water resources system and for integrating the strategic, tactical and emergency objectives of drought impacts management. A Multicriteria Decision-Analysis (MCDA) model is developed and used as tool of integration, which helps identify the timing and sequencing of the alternatives actions most relevant to the management objectives. Water resources managers may use the model in the preliminary phase of drought impacts management planning or as tool for implementing a drought plan. Two methods proposed by the Delft Hydraulic Laboratory in the Netherlands (ASCE, 1998) for sustainability assessment are applied. One is the *Weighted Statistical Indices* method to be

applied to the river system. For the second method, the MCDA model uses a modified version of the *Weighted Criteria Indices* method for assessing the relevance and sustainability of alternative options available for drought impacts management.

Zan N. Traoré  
Civil Engineering Department  
Colorado State University  
Fort Collins, Colorado 80523  
Spring 2005

**“With a dose of patience, one may have chance to see egg  
grow hair.”**

- Bamana proverb -

## **Acknowledgement**

I would like to heartily recognize all those who, one way or another have contributed to the successful completion of my study programs at Colorado State University.

For providing me with the financial support for my Master's degree and part of this PhD program, I would like to express my sincere gratitude to the Danish Agency for International Development (Danida). For her unconditional help and true commitment to my advanced education, I feel very indebted to Bente Schiller.

To the International School for Water Resources (ISWR), CSU, I owe very much for walking me through the admission process. For awarding me two scholarships when I most needed help in the course of my PhD program, I am grateful to the Department of Civil Engineering.

Since I left Mali in 1995, the *Direction Nationale de l'Hydraulique*, Bamako, Mali and its regional office in Sikasso, have helped my family and me in many ways. Therefore, I would like my colleagues and friends who manifested their solidarity toward us to find through these words the expression of our sincere appreciation of their efforts.

I am grateful to all members of my Graduate committee for their support, patience, and understanding. I would like to express special thanks to my advisor Dr. Darrel G. Fontane for his guidance, support, and encouragement, which all helped me attend the graduate school at CSU and achieve this work; without his mentoring, perseverance and constant availability, there would be no chance for this to happen. For his assistance to get me into the graduate school, and advice throughout the course of my stay at Colorado State University, I would like to extend my special thanks to Dr. Neil Grigg. My hearty thanks are also due to Dr. Freeman Smith and Dr. Timothy Gates for their time and contributions to this work.

To Marilee Rowe and Laurie Howard of the Civil Engineering Department, I want to convey my deep sense of gratitude for their solicitude during my entire journey at Colorado State University.

To Donnie Dustin, I would like to address my sincere thanks for assisting me in the application of the model.

For providing me with care and support in my long struggle to recover my health, I am greatly grateful to Dr. Thomas Dieringer and, through him, to all the medical personnel at the Hartshorn Health Services and elsewhere.

## **Dedication**

For their diverse contributions to my entire life, dedicating this work is my humble way of paying tribute to:

- ✓ My great grandfather Tiecouraba Traoré, and, through him, to all my Bamana ancestors of Daban, my village in Mali for providing me with an inexhaustible source of inspiration;
- ✓ My late grandmother Kiniba for her role in my early life;
- ✓ My late grandmother Midiè Kafene Diarra for giving me the affection that nothing else has made up since her passing away in May 1971;
- ✓ My late uncle N'Golofing Traoré of Daban for giving me the unique opportunity to go to school. There is no word, enough to express my deep sense of gratitude for his constant encouragement to pursue my education. His confidence in me meant more than support.
- ✓ My parents for consenting a great deal of sacrifices for me. My father N'Tio-blén Traoré showed me in the family farm how, with perseverance and patience, one could get the hardest work done right. To him, difficulties are no excuse for compromising the truth, quality and honesty. My mother Noumoudion Coulibaly repeatedly told me to always remember that a wife is a partner, not a property or tool to be used at will. My surrogate mother Flamou Tougouté did the best she could for me.

- ✓ All members of my extended Ferela family, Daban who made all the resources available to me in my primary and high school years;
- ✓ My first teacher Sidy Fomba who showed a great deal of patience to initiate me to the basic principle, value and virtue of learning;
- ✓ Lamine Traoré of Negala for introducing me to the family of his sister Mariam Traoré;
- ✓ Ba Mariam Traoré and her children of the Diakité family, Negala, Mali who, by adopting me as member of their family, made a significant contribution to my success at school;
- ✓ My family for their understanding and tolerance of my long absence. My wife Aïssata Touré, since our marriage in 1986, has devoted her entire time and energy to our family. For her consented sacrifices and privations, I owe her so much. For her unique contribution, a fair share of any credit for this work is due to her. Our children, Fatoumata Ferrey Traoré, Mohamed Cheick Omar Badian Traoré, Yaya Papa Traoré, Famougoury Moussa Traoré, and Sytapha Younoussa Traoré have shown a great deal of patience, restraint and perseverance;
- ✓ My late boss Sytapha Traoré, for giving me the opportunity to be where I am.

## TABLE OF CONTENTS

ABSTRACT.....	iii
ACKNOWLEDGEMENT.....	vii
DEDICATION.....	ix
TABLE OF CONTENT.....	xi
LIST OF TABLES.....	xv
LIST OF FIGURES.....	xix
<b>Chapter 1: INTRODUCTION</b>	
1.1. BACKGROUND.....	1-1
1.2. PROBLEM DEFINITION.....	1-3
1.3. RESEARCH GOALS AND OBJECTIVES.....	1-4
1.4. CONTRIBUTION.....	1-5
1.5. STRUCTURE OF THE STUDY.....	1-5
<b>Chapter 2: REVIEW OF LITERATURE</b>	
2.1. DROUGHT CONCEPT, DEFINITION AND PERCEPTION.....	2-1
2.1.1. Defining drought.....	2-1
2.1.2. Water shortage, scarcity, stress and security.....	2-4
2.2. DROUGHT ANALYSIS.....	2-5
2.2.1. Drought characteristics: the run theory.....	2-10
2.2.2. Drought prediction and forecasting.....	2-11
2.2.3. Drought early detection and warning.....	2-14
2.2.4. Drought impacts assessment.....	2-15
2.2.4.1. Approaches to the assessment of drought risk and impacts.....	2-15
2.2.4.2. Vulnerability, adaptation and adjustment capacity to drought.....	2-16
2.2.4.3. Approaches and methodologies for drought impacts planning and management.....	2-18
2.2.4.4. Contingency planning.....	2-19
2.2.4.5. Application of Decision Support and Expert Systems to drought management.....	2-21
2.3. DROUGHT IN THE SAHEL REGION, WEST AFRICA.....	2-22
2.3.1. Potential causes.....	2-23
2.3.1.1. Natural climatic variability and changes.....	2-23
2.3.1.2. Global warming and environmental degradation.....	2-24
2.3.1.3. Other hypothesis.....	2-25
2.3.2. Drought impacts.....	2-25
2.3.2.1. Impacts on water resources.....	2-25
2.3.2.2. Economic impacts.....	2-26

## TABLE OF CONTENTS (Continued)

2.3.2.3.	Environmental impacts.....	2-28
2.3.2.4.	Social impacts.....	2-29
2.3.3.	Drought-responses in the Sahel region.....	2-29
2.3.3.1.	National policies and strategies.....	2-29
2.3.3.2.	Regional coordination.....	2-30
2.3.3.3.	International cooperation.....	2-31

### Chapter 3

#### THE NIGER RIVER IN MALI: DROUGHT CHARACTERISTICS AND SUSTAINABILITY OF THE SYSTEM

3.1.	INTRODUCTION.....	3-1
3.2.	METHODOLOGY.....	3-5
3.3.	THE NIGER RIVER SYSTEM IN MALI.....	3-8
3.3.1.1.	Characteristics of flow deficits.....	3-11
3.3.1.2.	Statistics and distribution of the deficits, cumulative deficits and run lengths.....	3-19
3.3.1.3.	Flow sustainability.....	3-30
3.3.2.	The Bani River at Douna, Mali.....	3-33
3.3.2.1.	Characteristics of flow deficits.....	3-34
3.3.2.2.	Statistics and distribution of the deficits, cumulative deficits and run lengths.....	3-38
3.3.2.3.	Flow sustainability.....	3-43
3.3.3.	The Niger River at Mopti, Mali.....	3-46
3.3.3.1.	Characteristics of flow deficits.....	3-47
3.3.3.2.	Statistics and distribution of the deficits, cumulative deficits and run lengths.....	3-50
3.3.3.3.	Flow sustainability.....	3-61
3.3.4.	The Issa Ber at Dire, Mali.....	3-63
3.3.4.1.	Characteristics of flow deficits.....	3-64
3.3.4.2.	Statistics and distribution of the deficits, cumulative deficits and run lengths.....	3-69
3.3.4.3.	Flow sustainability.....	3-81
3.3.5.	Discussion of the results of the assessments.....	3-84
3.3.5.1.	Flow deficits.....	3-85
3.3.5.2.	Flow sustainability.....	3-88

## TABLE OF CONTENTS (Continued)

### Chapter 4: THE MULTICRITERIA DECISION MODEL (MCDA)

4.1.	MODEL DEVELOPMENT.....	4-1
4.1.1.	Approach.....	4-1
4.1.2.	Methodology.....	4-2
4.1.3.	The Model.....	4-6
4.1.3.1.	The criteria and sub-criteria.....	4-12
4.1.3.1.1.	Feasibility.....	4-12
4.1.3.1.2.	Sustainability.....	4-15
4.1.3.1.3.	Development opportunity.....	4-17
4.1.3.1.5.	The potential impact of the management option on the management objectives.....	4-19
4.1.3.2.	Model sensitivity.....	4-21
4.1.3.2.1.	Model sensitivity to drought severity.....	4-21
4.1.3.2.2.	Model sensitivity to the priority order of the management objectives.....	4-24
4.2.	MODEL APPLICATIONS.....	4-25
4.2.1.	Case study 1: Drought impacts management in Mali.....	4-25
4.2.1.1.	Assessment for different powers of compromise programming.....	4-25
4.2.1.1.1.	Model application to baseline conditions.....	4-28
4.2.1.1.2.	Model application with priority order 1.....	4-29
4.2.1.1.3.	Model application with priority order 2.....	4-31
4.2.1.1.4.	Model application with priority order 3.....	4-32
4.2.1.1.5.	Model sensitivity to drought severity.....	4-33
4.2.2.	Case study 2: Water supply and demand management for a Colorado city, USA.....	4-37
4.2.2.1.	Generality.....	4-37
4.2.2.2.	USA City Water supply and demand management.....	4-38
4.2.2.2.1.	Water demand management.....	4-39
4.2.2.2.2.	Water supply.....	4-40
4.2.2.2.3.	Water supply shortage response plan.....	4-40
4.2.2.2.4.	Regional cooperation.....	4-41
4.2.2.2.5.	Raw water quality.....	4-41
4.2.2.2.6.	Streamflow requirements.....	4-41
4.2.2.3.	Model application.....	4-42
4.2.2.3.1.	Management objectives.....	4-42
4.2.2.3.2.	Management alternative options.....	4-42
4.2.2.3.3.	Assessment results.....	4-43

## TABLE OF CONTENTS (Continued)

4.2.2.3.4.	Relevance and Sustainability Index.....	4-50
4.3.	Discussion of results.....	4-55
<b>Chapter 5: CONCLUSIONS AND RECOMMENDATIONS</b>		
5.1.	CONCLUSIONS.....	5-1
5.2.	CONTRIBUTIONS.....	5-9
5.3.	RECOMMENDATIONS.....	5-10
<b>References</b> .....		<b>R-1</b>

### APPENDIX

#### STATISTICAL STUDIES OF THE FLOWS OF THE NIGER RIVER IN THE INNER DELTA, MALI

1.	INTRODUCTION.....	A-1
1.1.	Climate.....	A-1
1.2.	Temperature, relative humidity and evapotranspiration.....	A-2
1.3.	Rainfall and water resources.....	A-3
2.	FLOWS CHARACTERISTICS.....	A-5
2.1.	The Niger River at Koulikoro gaging station.....	A-5
2.1.1.	Statistics and distribution of annual flows.....	A-7
2.1.2.	Correlogram of flows.....	A-13
2.2.	The Bani River at Douna, Mali.....	A-16
2.2.1.	Statistics and distribution of annual flows.....	A-16
2.2.2.	Corelogram of flows.....	A-22
2.3.	The Niger River at Mopti, Mali.....	A-25
2.3.1.	Statistics and distribution of annual flows.....	A-25
2.3.2.	Correlogram of flows.....	A-31
2.4.	The Issa Ber at Dire, Mali.....	A-33
2.4.1.	Statistics and distribution of annual flows.....	A-33
2.4.2.	Correlogram of flows.....	A-39

## LIST OF TABLES

Table 2.2-1: SPI classification values.....	2-4
Table 2.2-2: PHDI classification values.....	2-8
Table 2.2-3: RDI classification values	2-9
Table 3.3.1.1-1: Intensity of the deficits in the discharges of the Niger River at Koulikoro, Mali.....	3-16
Table 3.3.1.2-1: Statistics of the deficits in annual flows of the Niger River at Koulikoro.....	3-19
Table 3.3.1.2-2: Parameters of probability distribution functions fitted to the deficits in the annual flows of the Niger River at Koulikoro.....	3-22
Table 3.3.1.2-3: Probabilities distributions and return periods of the deficits in the annual flows of the Niger River at Koulikoro, Mali.....	3-24
Table 3.3.1.2-4: Probability distributions of the cumulative deficits in the annual flows.....	3-25
Table 3.3.1.2-5: Probability distributions of the run lengths of deficits in the annual flows.....	3-26
Table 3.3.1.3-1: Flow Sustainability Indices for the expected values of flow deficits and duration of deficit in the flows of the Niger River at Koulikoro, Mali.....	3-30
Table 3.3.1.3-2: Flow sustainability Indices of the Niger River at Koulikoro, Mali.....	3-31
Table 3.3.1.3-3: Ranking of flow types by sustainability indices.....	3-32
Table 3.3.2.1-1: Intensity of deficits in the flows of the Bani River at Douna, Mali.....	3-38
Table 3.3.2.2-1: Statistics of the deficits in the Flows of the Bani River at Douna, Mali.....	3-38
Table 3.3.2.2-2: Parameters of probability distribution functions of the deficits in the flows of the Bani River at Douna, Mali.....	3-40
Table 3.3.2.2-3: Probability distributions of the deficits in the flows of Bani River at Douna, Mali.....	3-41
Table 3.3.2.3-1: Flow Sustainability Indices for the expected values of flow deficits and duration of deficit in the flows of the Bani River at Douna, Mali.....	3-44
Table 3.3.2.3-2: Ranking of the flows by sustainability Indices of the Bani River at Douna, Mali.....	3-44
Table 3.3.2.3-3: Sustainability indices of the flows of the Bani River at Douna, Mali.....	3-45

## LIST OF TABLES (Continued)

Table 3.3.3.1-1: Intensity of deficits in the flows of the Niger River at Mopti.....	3-47
Table 3.3.3.2-1: Statistics of the deficits in the annual flows of the Niger River at Mopti, Mali.....	3-50
Table 3.3.3.2-2: Parameters of probability distribution functions of the deficits in the annual flows of the Niger River at Mopti, Mali.....	3-54
Table 3.3.3.2-3: Probability distributions of deficits in the flows of the Niger River at Mopti, Mali.....	3-55
Table 3.3.3.2-4: Probability distributions of the cumulative deficits in the flows of the Niger River at Mopti, Mali.....	3-56
Table 3.3.3.2-5: Probability distributions and return periods of run lengths of deficits in the annual flows of the Niger River, Mali.....	3-57
Table 3.3.3.3-1: Flow Sustainability Indices for the expected values of flow deficits and duration of deficit in the flows of the Niger River at Mopti, Mali.....	3-61
Table 3.3.3.3-2: Ranking of the flows by sustainability Indices of the Bani River at.....	3-62
Table 3.3.4.1-1: Intensity of deficits in the flows of the Issa Ber at Dire, Mali.....	3-68
Table 3.3.4.2-1: Statistics of deficits in the flows of the Issa Ber at Dire, Mali.....	3-69
Table 3.3.4.2-2: Parameters of probability distribution functions fitted to the deficits in the annual flows of the Issa Ber at Dire, Mali.....	3-73
Table 3.3.4.2-3: Probability distributions of the deficits in the flows of the Issa Ber at Dire, Mali.....	3-74
Table 3.3.4.2-3 (Continued): Probability distributions of the deficits in the flows of the Issa Ber at Dire, Mali.....	3-75
Table 3.3.4.2-4: Probability distributions of cumulative deficits in flows of the Issa Ber at Dire, Mali.....	3-76
Table 3.3.4.2-5: Probability distributions of the durations of deficits in the flows of the Issa Ber at Dire, Mali.....	3-77
Table 3.3.4.3-1: Flow Sustainability Indices for the expected values of flow deficits and duration of deficit in the flows of the Issa Ber at Dire, Mali.....	3-81

## LIST OF TABLES (Continued)

Table 3.3.4.3-2: Ranking of the flow types by flow sustainability Indices.....	3-82
Table 3.3.4.3-3: Flow sustainability indices of flows of the Issa Ber at Dire, Mali.....	3-83
Table 3.3.5.1-1: Summary of the intensity of deficits in the flows at different gaging stations.....	3-87
Table 4.1.3-1: Definition of Drought Preparedness Planning objectives.....	4-7
Table 4.1.3-2: Potential management responses to drought in the USA.....	4-9
Table 4.1.3.1-1: Rating scale of management alternative measures for criteria and sub-criteria.....	4-21
Table 4.1.3.2.1-1: Standardized Precipitation Index (SPI) values and corresponding drought intensity.....	4-22
Table 4.1.3.2.1-2: Weight of management for different drought Scenarios.....	4-24
Table 4.2.1.1-1: Weights of management objectives for different priority orders.....	4-26
Table 4.2.1.1-2: Results of assessment.....	4-27
Table 4.2.1.1.1-1: Assessment results for baseline conditions.....	4-28
Table 4.2.1.1.2-1: Results of model application for priority order 1.....	4-30
Table 4.2.1.1.3-1: Results of model application for priority order 2.....	4-32
Table 4.2.1.1.4-1: Results of model application for priority order 3.....	4-33
Table 4.2.1.2-1: Compromise programming ( $p = 1$ ) results for the baseline.....	4-34
Table 4.2.1.2-2: Ranking summary table.....	4-36
Table 4.2.2.3.3-1: Results of the qualitative assessment by the City water resources engineer.....	4-44
Table 4.2.2.3.3-2: Conversion of qualitative attributes into quantitative values.....	4-46
Table 4.2.2.3.3-3: Results of Compromise Programming ( $p = 1$ ).....	4-47
Table 4.2.2.3.4-1: RSI and ranking of alternative options.....	4-51
Table 4.2.2.3.4-2: Priority order of criteria and sub-criteria.....	4-53
Table 4.2.2.3.4-3: Results of the model application with the priority order defined by the engineer.....	4-54

## LIST OF TABLES (Continued)

Table A-1.2-1: Average monthly temperatures (°c) at stations in different climatic zones.....	A-2
Table A-1.2-2: Relative humidity average monthly values (%)	A-3
Table A-1.2-3: Average monthly values (mm) of evaporation and evapotranspiration .....	A-3
Table A-1.3-1: Rainfall average monthly values (mm).....	A-4
Table A-2.1.1-1: Statistics of the annual flows of the Niger River at Koulikoro, Mali.....	A-7
Table A-2.1.1-2: Probability distributions of the flows of the Niger River at Koulikoro, Mali.....	A-10
Table A-2.1.1-2 (Continued): Probability distributions of the flows of the Niger River at Koulikoro, Mali.....	A-11
Table A-2.1.2-1: Autocorrelation coefficients of annual flows of the Niger River at Koulikoro, Mali.....	A-14
Table A-2.2.1-1: Statistics of the annual flows of the Bani River at Douna, Mali.....	A-16
Table A-2.2.1-2: Probability distributions of flows of the Bani River at Douna, Mali.....	A-20
Table A-2.2.2-1: Autocorrelation coefficients of flows of the Bani River at Douna, Mali.....	A-22
Table A-2.3.1-1: Statistics of annual flows of the Niger River at Mopti, Mali.....	A-25
Table A-2.3.1-2: Probability distributions of flows of the Niger River at Mopti, Mali.....	A-28
Table A-2.3.1-2 (Continued): Probability distributions of flows of the Niger River at Mopti, Mali.....	A-29
Table A-2.3.2-1: Autocorrelation of the annual flows of the Niger River at Mopti, Mali.....	A-31
Table A-2.4.1-1: Statistics of the annual flows of the Issa Ber at Dire, Mali.....	A-33
Table A-2.4.1-2: Probability distributions of flows of the Issa Ber at Dire, Mali.....	A-36
Table A-2.4.1-2 (Continued): Probability distributions of flows of the Issa Ber at Dire, Mali.....	A-37
Table A-2.4.2-1: Autocorrelation and cross-correlation of annual flows of the Issa Ber at Dire, Mali.....	A-39

## LIST OF FIGURES

Figure 3.1-1: Flows of the Niger and Bani Rivers at different gaging stations.....	3-4
Figure 3.3.1.1-1: Excess or deficit in the annual flows of the Niger River at Koulikoro, Mali.....	3-12
Figure 3.3.1.1-2: Intensity of flow excess or deficit in flows of the Niger River at Koulikoro, Mali.....	3-13
Figure 3.3.1.1-3: Histograms of the deficits in the flows of the Niger River at Koulikoro.....	3-15
Figure 3.3.1.1-4: Histograms of the cumulative deficits in the annual flows of the Niger River at Koulikoro.....	3-17
Figure 3.3.1.1-5: Histograms of the durations of the deficits in the flows of the Niger River at Koulikoro, Mali.....	3-18
Figure 3.3.1.2-1: CDFs of probability distributions of the deficits in the flows of the Niger River at Koulikoro, Mali.....	3-27
Figure 3.3.1.2-2: CDFs of probability distributions of the cumulative deficits in the flows of the Niger River at Koulikoro, Mali.....	3-28
Figure 3.3.1.2-3: CDFs of probability distributions of the run lengths of deficits in the flows of the Niger River at Koulikoro, Mali.....	3-29
Figure 3.3.1.3-1: Sustainability indices of flows of the Niger River at Koulikoro, Mali.....	3-33
Figure 3.3.2-1: Annual flows of the Bani River at Douna, Mali.....	3-35
Figure 3.3.2.1-1: Excess or deficits in flows of the Bani River at Douna, Mali.....	3-36
Figure 3.3.2.1-2: Intensity of deficit or excess in the flows of the Bani River at Douna, Mali.....	3-37
Figure 3.3.2.1-3: Histograms of the deficits in the flows of the Bani River at Douna, Mali.....	3-39
Figure 3.3.2.2-2: CDFs of probability distributions of the deficits in the flows of the Bani River at Douna, Mali.....	3-42
Figure 3.3.2.3-1: Sustainability Indices of different flow types of the Bani River at Douna, Mali.....	3-46
Figure 3.3.3.1-1: Excess or deficits in the annual flow of the Niger River at Mopti, Mali.....	3-48
Figure 3.3.3.1-2: Intensity of excess or deficit in the flows of the Niger River at Mopti, Mali.....	3-49
Figure 3.3.3.2-1: Histogram of flow deficits of the Niger River at Mopti, Mali.....	3-51
Figure 3.3.3.2-2: Histogram of cumulative deficits in the flow of the Niger River at Mopti, Mali.....	3-52

## LIST OF FIGURES (Continued)

Figure 3.3.3.2-3: Histogram of the durations of deficits in flows of the Niger River at Mopti, Mali.....	3-53
Figure 3.3.3.2-4: Probability functions of the deficits in the annual flows of the Niger River at Mopti, Mali.....	3-58
Figure 3.3.3.2-5: Probability distributions of cumulative deficits of the Niger River at Mopti, Mali.....	3-60
Figure 3.3.3.2-6: Empirical and fitted probability distributions of durations of deficits in flows of the Niger River at Mopti, Mali.....	3-60
Figure 3.3.3.3-1: Sustainability Indices of the different flow types of the Niger River at Mopti, Mali.....	3-63
Figure 3.3.4-1: Annual flows of the Issa Ber at Dire, Mali.....	3-65
Figure 3.3.4.1-1: Flow excess or deficits of the Issa Ber at Dire, Mali....	3-66
Figure 3.3.4.1-2: Intensity of excess or deficit in flows of the Issa Ber at Dire, Mali.....	3-67
Figure 3.3.4.2-1: Histograms of deficits in the flows of the Issa Ber at Dire, Mali.....	3-70
Figure 3.3.4.2-2: Histograms of cumulative deficit in the flows of the Issa Ber at Dire, Mali.....	3-71
Figure 3.3.4.2-3: Histograms of run length of deficits in flows of the Issa Ber at Dire, Mali.....	3-72
Figure 3.3.4.2-4: Probability distributions of deficits in flows of the Issa Ber at Dire, Mali.....	3-78
Figure 3.3.4.2-5: Probability distributions of the cumulative deficits in the flows of the Issa Ber at Dire, Mali.....	3-79
Figure 3.3.4.2-6: Probability distributions of the durations of deficits in the flows of the Issa Ber at Dire, Mali.....	3-80
Figure 3.3.4.3-1: Sustainability Indices of different flow types of the Issa Ber at Dire, Mali.....	3-81
Figure 4.1.2-1: Flow chart of the strategy for the sustainable management of drought impacts .....	4-4
Figure 4.1.3-1: The Model of drought impacts management.....	4-6
Figure 4.1.3-2: Example pages of the Excel spreadsheet of the Model...	4-10
Figure 4.2.2.3.3-1: Ranking of the alternative options for water supply and demand management in the City.....	4-48
Figure 4.2.2.3.3-2: Ranking of the alternative options for water supply and demand management in the City.....	4-50
Figure 4.2.2.3.4-2: Relevance and Sustainability Index of alternative options.....	4-51

## **LIST OF FIGURES (Continued)**

Figure 4.2.2.3.4-3: Ranking of alternative options for the Strategic management defined by the model and the City water engineer.....	4-54
Figure A-2.1-1: Flows of the Niger River at Koulikoro, Mali.....	A-6
Figure A-2.1.1-1: Histograms of the annual flows of the Niger River at Koulikoro Mali.....	A-9
Figure A-2.1.1-2: CDFs of probability distributions of the flows of the Niger River at Koulikoro, Mali.....	A-12
Figure A-2.1.2-1: Autocorrelation of flows of the Niger River at Koulikoro, Mali.....	A-15
Figure A-2.2.1-1: Flows of the Bani River at Douna, Mali.....	A-17
Figure A-2.2.1-2: Histograms of the flows of the Bani River at Douna, Mali.....	A-18
Figure A-2.2.1-3: CDFs of the probability distributions of the flows of the Bani River at Douna, Mali.....	A-21
Figure A-2.2.2-1: Autocorrelation of flows of the Bani River at Koulikoro.....	A-24
Figure A-2.3.1-1: Annual flows of the Niger River at Mopti, Mali.....	A-26
Figure A-2.3.1-2: Histograms of flows of the Bani River at Mopti, Mali...	A-27
Figure A-2.3.1-3: Probability distributions of flows of the Niger River at Mopti, Mali.....	A-30
Figure A-2.3.2-1: Autocorrelation of flows of the Niger River at Mopti, Mali.....	A-32
Figure A-2.4.1-1: Annual flows of the Issa Ber at Dire, Mali.....	A-34
Figure A-2.4.1-2: Histograms of annual flows of the Issa Ber at Dire, Mali.....	A-35
Figure A-2.4.1-3: CDFs of probability distributions of the annual flows of the Issa Ber at Dire, Mali.....	A-38
Figure A-2.4.2-1: Auto-correlation of flows of the Issa Ber at Dire, Mali	A-40
Figure A-2.4.2-2: Cross-correlation of flows of the Issa Ber at Dire, Mali.....	A-41

## **CHAPTER 1: INTRODUCTION**

### **1.1. BACKGROUND**

Droughts are occurring in different regions of the world with increased frequency and severity. As a result, many communities such as those of Sahel region of West Africa have been struggling with the challenge of meeting their increasing water demands with shrinking resources. In that particular region, the relatively wet period of the 1950s was followed by a series of drought sequences that caused severe food and water shortages. At their climax in 1973 and 1984, those shortages claimed many lives in affected countries. In addition to dealing with the immediate impacts of the crisis, the issue for the region was to define and implement strategies that may minimize the risk for future droughts. In order to achieve this strategic goal of drought impacts management, the affected countries and their partners took different policy initiatives. However, the increased recurrence of drought and the persistence of its impacts have challenged the wisdom of emergency interventions and the achievement of the strategic objectives (Wilhite, 1990, 2000.)

Agenda 21 (The Earth Summit, 1992) and other forum have recommended drought contingency planning as proposed by researchers. In support of this reorientation of drought impacts management on a global scale, the United Nations has set up the Convention to Combat Desertification and the effects

of Drought (UN-CCD.) The UN-CCD is meant to help various countries around the world to develop and implement their National Actions Programs, including contingency planning. To achieve this objective, different planning frameworks have been proposed for the comprehensive management of drought impacts. By applying the proposed planning frameworks, many states in the USA and other countries have defined their contingency plans for drought impacts management.

As part of its assistance to Sub-Saharan African countries, the UN-CCD sponsored an assessment of the status of drought impacts planning and management in a certain number of countries. (Wilhite, 1999.) The assessment identified two major constraints to the attainment of drought impacts management goals: the absence of contingency planning and the limited priority given to the strategic objectives. Therefore, the mission recommended the adoption of a planning framework, which is, to certain extent, similar to the one already in use in some states of the USA where other planning frameworks have been proposed for drought impacts management too.

A review of the planning framework proposed to African countries shows that some critical issues remain to be addressed. Among other things, it would be crucial to assess the status of the water resources system in terms of sustainability with respect to the supplies, demands and other constraints. In case the system proves unsustainable before the occurrence of drought, the

scope of the problem to deal with may go beyond only planning for mitigating drought impacts, and require a redefinition of the whole scheme of resources management. Under drought conditions, the issue is to define the operational strategy to implement in order to achieve the most effective management of the impacts.

## **1.2. PROBLEM DEFINITION**

As mentioned above, the planning framework proposed to African countries as well as the other planning frameworks found in the literature may well serve to define drought contingency plans.

However, despite the potential for such contingency plans to achieve certain goals of drought impacts management, their implementation may prove challenging. In particular, it would be critical for water resources managers to determine to what extent the water resources system can sustain current and future demands before drought sets in. The next challenge would be to make the decision of what alternative options to implement at what phase of a developing drought. Depending on the intensity and duration of drought, the affected area and the state of the water resources system, the different management goals and objectives may vary over time and space. Similarly, there may be different alternative actions available for achieving those objectives. In the context defined above, the strategic objectives of drought impacts management may include:

- 1) Defining a management scheme for the water resources system under consideration that should lead the system to achieve sustainability before drought occurs;
- 2) Determining the sustainability and degree of relevance of all alternative actions with potential for the management of drought impacts at any degree of drought severity;
- 3) Defining a course of action that achieves consistency in the management of the impacts before, during and after a drought.

As explained in the next sub-section, the objectives of this study are to propose answers to these issues, which would be critical to the success of drought impacts management, especially for the long term.

### **1.3. RESEARCH GOALS AND OBJECTIVES**

To address the problems identified above, this research had the goal of defining a procedure for integrating the strategic, tactical and emergency management of drought impacts, especially in developing countries. In specific terms, the research:

- ✓ Applied one sustainability theory to the assessment of the water resources system with regard to the supplies, demands and other environmental considerations;
- ✓ Applied the second sustainability theory to the management alternative options available for implementation in a comprehensive management of drought impacts. To do this, a MultiCriteria Decision

Analysis (MCDA) spreadsheet model was developed and used to determine the relevance and sustainability of potential management actions;

- ✓ Based on the relevance and sustainability degree of the management actions, a dynamic strategy that adapts the management to drought severity was defined. In essence, the strategy consists of designing the timing and sequencing of the implementation of the most relevant management options such that the objectives of drought impacts management are consistent with the level of drought severity and with the strategic management.

#### **1.4. CONTRIBUTION**

By addressing the challenges mentioned above, this study is, in extension of the "*what to do*" dealt with by the contingency planning, bringing an answer to the questions "*how to do and when to do*" of drought impacts management. The relevance and sustainability index provides the opportunity to design a course of action that is consistent in terms of timing and sequencing of the implementation of selected management alternatives, and with the long-term objectives of drought impacts management.

#### **1.5. STRUCTURE OF THE STUDY**

As stated above, the objectives of defining a strategy of drought impacts management dictate the following organization of the study:

- ✓ The review of relevant literature;
- ✓ The assessment of drought characteristics in the Niger River system in its course in Mali;
- ✓ The development of the MCDA Model for drought impacts management;
- ✓ Case studies of the model application;
- ✓ Conclusions and recommendations.

## **Chapter 2: REVIEW OF LITERATURE**

### **2.1. DROUGHT CONCEPT, DEFINITION AND PERCEPTION**

Historical accounts and recent paleo reconstructions all suggest that, at different times in the past, the climate has gone through variability and changes on a local, regional, or global scale (Smith et al., 1996.) Among the extreme events, which have marked the climate, drought is one that has occurred recurrently with dire consequences. For the scientific and professional communities, and the public at large, drought is characterized by its unpredictable occurrence and development with pervasive and diffuse impacts (Wilhite, 2000.) Therefore, understanding drought remains a challenge to specialists as well as to the public. This persistent lack of understanding of drought is identified as one of the major constraints to the mitigation of its impacts, which may include water and food shortages. This study and the following review deal mainly with how to manage water shortage as results of drought.

#### **2.1.1. Defining drought**

As Wilhite (2000) has pointed out, there is a variety of definitions used to convey the concept of the drought phenomena. Based on a review of drought-related literature, Wilhite et al. (1987) found more than 150 definitions of drought. According to the review, drought definitions may be

classified in either of two main categories: conceptual and operational.

Conceptual definitions may convey the notion by a generic description of the drought and its characteristics; this category of definitions may help refine the understanding of the phenomenon, but are not specific enough to define the start and end of a given drought sequence. Operational definitions try to convey the notion of drought by giving accurate information on the characteristics of the phenomenon and the threshold values of its underlying variables; this second type of definitions may be of help for designing drought management policies and strategies.

Wilhite D. (2000), has distinguished four sub-categories of the operational definitions of drought:

- ✓ *Meteorological (climatological) droughts* are defined in terms of deficit and/or abnormal distribution of rainfall with reference to a normal or average value for the time interval under consideration; the following definition may fall into this category: "Drought implies an extended and significant negative departure in rainfall, relative to the regime around which society has established" (Rasmusson, 1987;)
- ✓ *Agricultural droughts* are defined in terms of soil moisture deficit, and/or of the ratio of actual and potential evapotranspirations; these definitions are crop and growth stage specific. In a way, agricultural droughts may be seen as the impacts of meteorological droughts on agriculture.

- ✓ Hydrological droughts represent the deficits in water volume or discharge with reference to some expected levels of surface water, groundwater and planned reservoir storage, and streamflows.

The U.N. Convention to Combat Desertification and Drought (UN-CCD, 1994) has a more conceptual type of drought definition: "Drought means the naturally occurring phenomenon that exists when precipitation has been significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production systems."

The absence of a single universally accepted definition of drought results in confusion, which is a major obstacle to the development and implementation of policies and strategies of drought impacts management (Wilhite, 2000.) Therefore, for operational purposes it is suggested that drought be defined with reference to the geographic location, impacts and the field of application (Wilhite, 2000.)

In addition to the controversy over the technical definitions, the perception of drought is another source of confusion. To Michael Mortimore (1989), the perception of drought is primarily determined by the extent to which drought impacts are felt in terms of unmet needs. In the case of the Sahel region, development policy makers' perception of drought as a "transient phenomenon" may have resulted in the non-integration of drought risk into National Development Plans (Glantz, 1987.)

### **2.1.1. Water shortage, scarcity, stress and security**

Instead of extending the search for a universal definition of drought, recent discussions have put the focus on using terms that express the degree of water availability (Len Abrams, 2000):

- ✓ Water shortage is defined to be the extent of water availability to which the minimum demands are not met (Abrams, 2000.) James T. Winpenny defines water shortage as “low levels of water supply relative to minimum levels necessary for basic needs” (FAO, 1995.) In both cases, water shortage is defined with respect to the levels of supply and demand. While the demand may be measured by per capita minimum, which varies widely between countries and within the same country, the supply may be measured by the renewable water resources available per capita. In the case of Mali, the Water Resources Development Master Scheme (“Schema Directeur de Mise en Valeur des Ressources en Eau du Mali”, DNHE, 1990) has established the minimum standards for the provision of supply services as:

- 20 liters/day/person for rural villages of less than 2000 inhabitants;
- 31 liters/day/person for rural towns of 2000 to 10000 inhabitants;
- 46 liters/day/person for cities of more than 10000 inhabitants;

- 54 liters/day/person for the capital city Bamako.

In 1995, the renewable water resources available in Mali were estimated to be 6207 m<sup>3</sup>/person/year.

- ✓ Water scarcity expresses the deficit in water supplies with respect to demands (Abrams, 2000.) It is an imbalance between water available and use (FAO, 1995.)
- ✓ Water stress is defined to be "the symptoms of water shortage or scarcity, which may include conflicts among water users, a deterioration in water services and crop production (FAO, 1995.)
- ✓ Water security is the extent to which the access to water is reliable and secure (Abrams, 1997.) In the non-developed world, water security is an important issue, which depends on different factors.

## 2.2. DROUGHT ANALYSIS

Methods developed for studying drought can be classified by (Salas, 1986):

- ✓ *The field of study* such as climatology, meteorology, hydrology, and agriculture;
- ✓ *Water or moisture variable of interest*, which may be rainfall, streamflow, soil moisture, reservoir level, and evapotranspiration;
- ✓ *The method of drought data analysis*: all disciplines combined, drought data analysis uses one or another of the following methods:
  - *Methods of empirical data analysis*, which use recorded drought data to estimate needed drought parameters; no theoretical model is involved;

- *Analytical drought analysis methods* use historical data of a water or moisture variable to fit a theoretical model, which best describes the occurrence or distribution of the variable, and allows drought analysis;
- *Data generation methods* use statistical properties derived from historical data record of a water or moisture variable in order to generate likely sequences of its future occurrences;
- *Indices drought data analysis methods* compute and compare the actual value of an aggregate index (combining one or more water/moisture variables) with a pre-established dimensionless drought severity scale. Indexes are objective measures used to characterize a drought sequence. In a review, Hayes M.J. (1999) reported the following methods of defining and computing different drought severity indices:
  - ❖ *The Percent of Normal* is the departure (percent) of the actual precipitation at a given location and time from the normal precipitation value understood to be the 30-year mean. It is computed by dividing the actual precipitation by the normal precipitation. The non-normal distribution of rainfall and the confusion arising from the normal distribution implied by the name "normal precipitation" are the major problems associated with the use of this index, which is easy to compute and can help assess the status of drought at regional or seasonal scales.

- ❖ *The Standardized Precipitation Index ("SPI")* expresses the impacts of precipitation deficit on water resources for different time scales (McKee et al., 1993).

SPI Values	
2.0 +	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-.99 to .99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
-2 and less	Extremely dry

Table 2.2-1: SPI classification values (Source: Hayes 1999)

The computation of the SPI at a given location involves fitting a probability distribution function to the standardized and normalized precipitation time series of the location; the mean SPI will be zero for the location and period under consideration. Negative (positive) SPI values represent drier (wetter) periods. The SPI may be a useful drought assessment tool for the early detection and warning in the Sahel region.

- ❖ *The Palmer Drought Severity Index (PDSI)* is a meteorological drought index developed by Palmer in 1965. It is computed by using a water balance equation, with the terms of precipitation, temperature, and available water content. In the short term, the equation

of water balance is limited to moisture flux (inflow-outflow), and the resulting PDSI becomes the Palmer Hydrological Drought Index (PHDI).

Palmer Classifications	
4.0 or more	Extremely wet
3.0 to 3.99	Very wet
2.0 to 2.99	Moderately wet
1.0 to 1.99	Slightly wet
0.5 to 0.99	Incipient wet spell
0.49 to -0.49	Near normal
-0.5 to -0.99	Incipient dry spell
-1.0 to -1.99	Mild drought
-2.0 to -2.99	Moderate drought
-3.0 to -3.99	Severe drought
-4.0 or less	Extreme drought

Table 2.2-2: PHDI classification values (Source: Hayes 1999)

Hayes (1999), noted that, due to the high variability of precipitation in Australia and South Africa, applications of the PDSI did not produce satisfactory results. For the same reason, the PDSI may not be a good suggestion for the Sahel region;

- ❖ The *Crop Moisture Index (CMI)* is defined by procedures similar to those used for the PDSI; it is used to monitor week-to-week changes in moisture conditions, and is limited to the crop-growing season.

- ❖ The *Surface Water Supply Index (SWSI)* is a basin and season-specific index using snow pack, precipitation, streamflow, and reservoir storage. The need for the SWSI to be reformulated for accommodating any changes in the basin's conditions is a limitation on its application. In addition, the occurrence of an extreme event with the value going beyond the range of variation defined by the time series of the historical data may make the established SWSI non-relevant.
- ❖ The *Reclamation Drought Index (RDI)* is similar to the SWSI but, in addition to the inputs for the SWSI, it also uses the temperature. Through the RDI, drought is characterized by its severity, duration, onset, and end. As for the SWSI, the RDI is basin-specific, therefore cannot be used for the purpose of interbasin evaluation of drought;

RDI Classifications	
4.0 or more	Extremely wet
1.5 to 4.0	Moderately wet
1 to 1.5	Normal to mild wetness
0 to -1.5	Normal to mild drought
-1.5 to -4.0	Moderate drought
-4.0 or less	Extreme drought

Table 2.2-3: RDI classification values (Source: Hayes 1999)

- ❖ The *Deciles* are the uniform drought watching method used by the Australian Drought Watch System for drought management decision-making.

- ✓ *Methods using drought spatial extent:* By using the extent criterion, a drought study is either regional (analyzing drought from data collected at different locations) or limited to a single location.
- ✓ *Analysis method using drought characteristics* is a drought study oriented to drought characteristics.

### **2.2.1. Drought characteristics: the run theory**

Researchers, depending on their needs for specific information, have used different types of drought characteristics as a basis for comparing drought events (Wilhite, 2000; Salas, 1986). Based on the run theory (Yevjevich, 1967), drought may have the following characteristics:

- ✓ *Drought initiation* is the precise time at which the chosen variable of water or moisture availability falls below a predefined minimum required value (threshold;)
- ✓ *Drought termination* is the time at which the value of the chosen variable of water or moisture availability is greater or equal to a predefined minimum required value (threshold;)
- ✓ *Drought duration* is the total length of time spanning between the times of drought initiation and termination;

- ✓ *Drought magnitude* is the deficit of water or moisture expressed in units of the chosen variable at a certain time. The total magnitude of a drought event might be expressed as the cumulative magnitude over drought duration. Spatial magnitude is expressed as the product of the magnitude at a specific point in time multiplied by the affected area;
- ✓ *Spatial coverage* is the geographical area where the shortage of water or moisture prevails with reference to the threshold value of the chosen variable.

It is obvious that the characteristics as described above are relative, which is they are defined with reference to an arbitrary threshold value of the variable of interest.

### **2.2.2. Drought prediction and forecasting**

Drought prediction includes all activities aimed at forecasting the occurrence of drought future events (Wilhite, 2000). The method of statistical forecasting, which is based on climate variability on seasonal, interannual and decadal scales, has been widely used for climate prediction. However, the development of climate scenarios that are based on General Circulation Models (GCMs) has recently received a greater attention from researchers. GCMs are particularly useful for assessing the potential impacts of climate change, which are likely to result from an accumulation of CO<sub>2</sub> and/or environmental degradation. Mays L.W. (1996) has reviewed some of the

methods used for developing climate scenarios; the following is a summary of his review:

- ✓ *Climate scenarios based on historical and spatial analogues:* historical analogues-based climate scenarios are using instrumental analogues (data of recorded temperature, precipitation and atmospheric pressure) or proxy analogues (climate data generated from known extreme events, paleoclimatology and dendrochronology) and doubled-CO<sub>2</sub> to develop future climate scenarios. The scarcity of climate data (unreliable quality and short length of existing meteorological/hydrological data records, and the deteriorating data collection networks) may be a constraint to the use of instrumental records in Africa (Sircoulon et al., 1999.) Spatial analogue-based climate scenarios are using the similarity between existing climate data of a given location and predicted future climatic conditions. Due to the particular pattern of atmospheric circulation and the suspected interaction of land surface and atmosphere in the Sahel region, finding other locations with similar climatic conditions to simulate future conditions of the Sahel may prove challenging.
- ✓ *Climate scenarios based on GCMs simulations* are the descriptive results of climate change simulated by an increasing accumulation of atmospheric carbon dioxide. The large scale of GCMs (O-GCMs and A-GCMs), their inability to incorporate the atmosphere-ocean-land surface interaction and the responses of those systems to the change are all sources of uncertainty, which makes the scenarios generated

less useful for practical purpose (Karpe, 1990; Sircoulon, 1999). In the context of Africa, the GCMs are not producing reliable results for greenhouse impacts on precipitation and environmental degradation (Sircoulon, 1999). Some of the problems related to large-scale modeling are addressed by the field experiments, which focus primarily on regional modeling for developing climate scenarios as illustrated by the EPSAT-Niger and HAPEX-Sahel projects being implemented in the Sahel region. The EPSAT-Niger field experiment (Sircoulon, 1999) is using a degree square area located in Niger and has three main objectives, which are: (1) to refine rainfall prediction in the Sahel using available data; (2) to better describe and model rainfall variation useful to climate prediction; and (3) to assess the impacts of rainfall variation on water resources of the Sahel. The World Climate Research Program has designed the HAPEX-Sahel program as part of its GEWEX initiative; the HAPEX-Sahel program is using the same area as the EPSAT-Sahel experiment. The HAPEX-Sahel program has the objective of providing a better understanding of the interaction between the land surface and atmosphere in order to incorporate it into GCMs;

- ✓ *Climate scenarios based on prescribed climate changes* are meant to reflect the responses to anticipated changes in temperature, precipitation, and evapotranspiration by global warming. As Larry W. Mays (1996) has noted, despite the potential for these climate scenarios to perform sensitivity analysis, they are incapable of

integrating the interaction between land surface and ocean, and atmosphere, as this interaction is the determinant in the climate of the Sahel region.

Due to the weakness of the procedures for developing climate scenarios as mentioned above, the combination of different methods is the new direction considered for exploration.

Again, given the critical role of the interaction between the continental land surface and the atmosphere in determining the climate of the Sahel, the integration of the environmental component in climate scenarios would be more reflective of the Sahelian reality as demonstrated by Xue and Shukla (1993). Therefore, instead of considering the problem of drought in terms of direct causes and impacts, it might be more realistic to use an interaction approach in order to deal with the relationship between drought and environmental degradation (Parry M. M., 1987).

### **2.2.3. Drought early detection and warning**

As Kelly T. Redmond (Wilhite, 2000) has pointed it out, the current state of the scientific knowledge and technology can hardly allow a climate prediction meaningful to drought early detection and warning. Therefore, the problem of drought early detection and warning has been addressed in many cases by monitoring the variations in the physical climate system and the impacts of those variations on the availability of water or moisture. Depending on the

objective of drought impacts management, different indices, as reviewed earlier above, may serve as an indicator of the drought status.

By developing and operating a drought-monitoring system, the Food and Agriculture Organization (FAO) of the United Nations meant to extend its Global Information and Early Warning System (GIEWS) to Africa; the monitoring system was a response to the food crisis, which afflicted many African countries in the 1980s. The Famine Early Warning System Network (FEWS NET) funded by US-AID and the Canadian Analysis of Drought in Africa (CANDAF) are both drought monitoring systems designed to provide Africa with food security management tools (Wilhite, 2000.)

#### **2.2.4. Drought impacts assessment**

##### **2.2.4.1. Approaches to the assessment of drought risk and impacts**

As mentioned earlier, the risk for a given natural hazard results from the potential for the hazard to happen and the vulnerability of the exposed groups or activities (Wilhite, 2000). The vulnerability, which is defined by Wilhite (2000) as the extent to which an individual or a community is exposed to the negative impacts of a natural hazard, is dynamic, and may result from the convergence of different factors.

Martin M. Parry et al. (Wilhite, 1987) identified two main approaches to the assessment of drought impacts. The impact approach assumes a direct cause-effect relationship between the hazard and the human activity, which sustains the impacts. The interaction approach, instead of the cause-effect relationship between the hazard and the human activity, assumes that the impacts sustained by human activity result from the interaction between different processes involving drought and the exposure unit. According to Martin M. Parry et al. (Wilhite, 1987), the application of the second approach to the case of the Sahel region shows that the crisis consecutive to the rainfall deficit results from the combination of many factors. Among other factors contributing to the crisis, the climate, social and economic conditions, and environmental systems have been identified; the approach may allow the modeling of the series of impacts resulting from successive orders of interaction between drought and the society.

#### **2.2.4.2. Vulnerability, adaptation and adjustment capacity to drought**

In macro economic terms, Benson and Clay (Wilhite, 2000) have shown that, due to the limited integration between their large agriculture and other economic sectors, most economies (presumed simple) of the Sahel region exhibit less sensitivity to drought. Because of the dynamic character of the vulnerability, Thomas E. Downing et al. (Wilhite, 2000) suggest that the indicators of vulnerability to drought be defined and monitored. The

vulnerability indicators may provide the basis for developing the needed strategies of adaptation and adjustment to drought impacts.

Despite the contrasting results of the General Circulation Models, the Intergovernmental Panel on Climate Change (1998) found that Africa in general, and the Sahel region in particular are likely to be more vulnerable to climate change than initially anticipated.

Adaptation and adjustment to drought may take two forms: tactical and strategic adjustments (U. S. Army Corps of Engineers, 1991). While tactical adjustment is a coping strategy, which considers drought as a crisis, strategic adjustment is a long-range strategy of drought risk management. For water resources, either adjustment strategy may involve structural or non-structural measures. The Intergovernmental Panel on Climate Change (IPCC), based on its assessment of the vulnerability of African countries to the impacts of potential climate change, found that the capacity of adaptation and adjustment of those countries to changes in water resources would depend on many factors (1998). Among other things, the IPCC has identified: (1) political stability, local initiative for development and achievement of sustainability in water resources management, (2) appropriate water resources development policy, legislation and strategies, and (3) availability of data and local capacity for assessing water resources (quantity and quality), and water demands. Sharma et al. (1996) used different criteria (the enabling environment, poverty degree, and population

access to water for drinking, sanitation, and irrigation) to determine country indicators of performance for addressing water issues. As result of the assessment, most countries of the Sahel exhibited poor performance levels.

#### **2.2.4.3. Approaches and methodologies for drought impacts planning and management**

The choice of drought planning objectives and management strategies is dependent on the perception of the phenomenon by affected people (Wilhite, 2000). The approaches to the definition of drought- responses are of three types (Richard W. Perrit, 1997):

- ✓ *The reactive or crisis management* approach designs responses based on the impacts, shortages and system failures already sustained; this approach results essentially from the perception of drought as a random natural hazard, thus inevitable. As mentioned earlier, until recently, this approach to drought management has prevailed in almost all countries, including those of the Sahel region.
- ✓ *The anticipatory or proactive* approach deals with drought by designing adjustment schemes well before drought occurrence. This approach considers drought as an expected feature of the climate; it requires lead-time and the investment of important resources, which are not always available to developing countries like those of the Sahel.

- ✓ The incremental approach consists of the combination of the proactive and reactive approaches; it provides for small-scale proactive or reactive adjustments.

Benedykt Dziegielewski (Wilhite, 2000) has used his formula of “Drought Protection Investment Tradeoff (DPITm)” to conduct a cost-benefit analysis of proactive drought management; he found that proactive adjustment is cost-effective compared to the strategy of reactive adjustment.

#### **2.2.4.4. Contingency planning**

Following the 1980s’ drought sequences in many states, the US Corps of Engineers undertook a “National Study of Water Management During Drought”; the study resulted in the development of a seven-step methodology for drought planning, which focuses on improving water management during drought.

In 1991, Wilhite suggested a ten-step framework for planning drought preparedness and mitigation in the USA; after assessing the status of drought preparedness in the USA, he found (2000) that only twenty-seven out of the fifty states had developed drought plans in 1997, and that six other states had their plans under development. The Colorado Drought Response Plan (1990) is one of the existing drought plans; it consists mainly of an assessment and response systems, which operate by relying mainly on state agencies.

In order to address the problem of water shortage during droughts in the U.S.A., Neil Grigg and Vlachos (1990) developed a mitigation and response framework that consists of three main responses categories, each encompassing specific strategies; the framework is summarized as follow:

- ✓ Supply augmentation may consist of such measures as system improvement/conservation, high flow skimming, interbasin transfer/import, conjunctive use, conveyance grids, technological innovation, etc. These measures could target existing, new or mixed supplies;
- ✓ Demand reduction is concerned with proactive, reactive and incremental adjustment measures, which may be legal measures, economic incentives, public education, water conservation, metering and all other changes in water uses. By nature, most demand reduction measures may not be very relevant to drought management in African countries where, even under normal conditions, water supply is barely enough to cover basic needs; currently, up to two-third of rural population and one-quarter of urban population have no access to safe drinking water and sanitation (IPCC, 1998). However, for demand reduction, measures such as legal measures, increasing pricing rate for additional consumption beyond nominal volume equivalent to essential needs, prioritizing water demands, and land use policies may have the potential of playing a meaningful role in drought impacts management in the Sahel region.

- ✓ Impact minimization may consist of implementing anticipatory strategies, loss absorption, and reduction. Anticipatory strategies may encompass a forecasting system, regulation of consumption, conflict resolution etc. Loss absorption is concerned with such measures as insurance, spreading of risk, and disaster relief. Loss reduction consists of damage recovery, event modification and changes in water uses. Most strategies of this response category may be relevant and applicable to drought management in the Sahel region.

#### **2.2.4.5. Application of Decision Support and Expert Systems to drought impacts management**

Christos Alexander Karavatis (1992) has proposed a proactive and comprehensive approach to drought impacts management in the metropolitan area of Athens, Greece. The new approach uses knowledge-based system (KBS) and system analysis as an aid to decision-making for drought management. In extension to this approach, he has suggested (1999) a DSS for drought management strategies in the Metropolitan Athens.

For daily drought monitoring, Tiao J. Chang et al. (1996) have developed a Clips-based Expert System and successfully applied it to the historic drought that occurred in Ohio in 1998.

### **2.3. DROUGHT IN THE SAHEL REGION, WEST AFRICA**

Eugene M. Rasmusson (Glandz, 1986) has identified two patterns of deficit in rainfall data of West Africa. According to him, a pattern of short-term (1 to 3 years) and severe drought sequences is associated with the variability of the oceanic and atmospheric circulations on a global-scale. He has also found a correlation between the anomalies in sea surface temperature (SST) of the South and North tropical Atlantic Ocean, and the interannual variability (drier and wetter years) of rainfall in West Africa, and in Northeastern Brazil. The second pattern consists of drought sequences lasting about a decade; this pattern has characterized rainfall in West Africa since the 1960s. These drought sequences, occurring with a trend of increasing severity, may be associated with the gradient of SST of the Atlantic Ocean at the tropics. While the short sequences of drought are believed to be the manifestation of interannual variability in the climate, long sequences of drought may be the expression of a climate change (Rasmusson, 1986; Sircoulon, 1999).

By reviewing paleoclimatological studies of the Sahel region, Sircoulon, J. (Van Dam, 1999) has identified significant temporal fluctuations in temperature and rainfall. Based on the results, he, too, has drawn the conclusion that drought sequences of different length and severity have always been experienced in the Sahelian climate. However, the trend of increasing severity of recent droughts, their persistence and frequent

recurrence and their suspected correlation with anthropogenic activities on the climate has set them apart.

### **2.3.1. Potential causes**

Understanding the causes of drought or factors that may be triggering rainfall deficiency is critical to any planning and management efforts of drought impacts. However, like defining its real nature, identifying the causes of drought remains a challenge for the scientific community and policy makers alike. For Africa in general, the complexity of the mechanisms generating rainfall, and the lack of reliable data all add to the difficulties of identifying the causes of drought (Glandz, 1986.) For the Sahel region in particular, the suspected impact of the land surface on the different processes leading to rainfall may be one of the main sources of complexity. Due to the difficulty of isolating specific triggers of drought, recent efforts on drought research have been exploring the possibility of correlation between the fluctuations in rainfall and other factors.

#### **2.3.1.1. Natural climatic variability and changes**

As mentioned before, climate variability in Africa is suspected to be a source of the fluctuations in rainfall. This variability, in turn, may be associated with the global-scale ocean-atmospheric circulation, which results in the ENSO for the Pacific region and variations in sea surface temperature for the Atlantic Ocean.

### **2.3.1.2. Global warming and environmental degradation**

Following studies that suggest a positive correlation between the continuing accumulation of CO<sub>2</sub> and the increase in the temperature on a global scale, a comprehensive assessment was needed (Mays L., 1996). In response, the UN created in 1988 the Intergovernmental Panel on Climate Change (IPCC) and charged it with the responsibility of reviewing the scientific knowledge on climate change and its potential impacts worldwide (Jan C. Van Dam, 1999.) For the Sahel region the assessment of changes in the climate during the last 100 years shows (Sircoulon, 1999):

- ✓ A cumulative increase of 0.53 °C in the temperature;
- ✓ An important fluctuation in the rainfall resulting in three drought sequences (in the 1910s, 1940s and 1960s); and
- ✓ Significant runoff deficits in all river basins.

However, Sircoulon (1999) has noted that, due to conflicting conclusions on the impacts of global warming on rainfall in the Sahel region, the results may not be ready for use in actual climate prediction.

An increasing number of researchers (Charney, 1975; Xue and Shukla, 1993; IUCN, 1992) are also suspecting environmental degradation in the Sahel as a factor playing a major role in the current prolonged drought. Actually, the destruction of vegetation cover may result in the reduction of soil moisture, soil erosion and increased albedo (Sircoulon, 1999).

### **2.3.1.3. Other hypothesis**

In addition to the climate variability and climate change identified as potential triggers of drought, Nick Brook (1999) has explored a third hypothesis on the causes of rainfall deficiency in the Sahel. By using the Infra-red Difference Dust Index (IDDI) to determine the sources and the spatial distribution of atmospheric dust in the Sahara, he found that the primary source of the dust is the Sahara desert itself and its transition zone with the Sahel. According to him, on an interannual timescale, the dynamic interaction between the land surface and atmosphere is the primary cause of dust production, which in return has an impact on the thermal characteristics of the atmosphere, and subsequently on the rainfall regime.

### **2.3.2. Drought impacts**

By its very diffuse nature, drought may cause direct and indirect damages to different sectors in affected areas (Wilhite, 1993; 2000.) Drought impacts may fall in one of the following three categories: economic, social, and environmental.

#### **2.3.2.1. Impacts on water resources**

Sircoulon (2000) has noticed a decrease of 20 to 40% of the mean rainfall of the Sahel region between the periods 1931-60 and 1961-90. According to him, the reduction in rainfall has resulted in:

- ✓ The southward shift of isohyets by a 100 km;
- ✓ Runoff deficit for the main rivers with the consequence of significant changes in their flow regimes;
- ✓ Increase in runoff coefficient and depletion coefficient of aquifers in major river basins.

An assessment of drought impacts on the Niger River in its course in Mali is presented in chapter 3 as part of this research.

### **2.3.2.2. Economic impacts**

For developing countries like those of the Sahel region, drought impacts on the whole economy may be so diffuse that it might not be easy to discriminate them from the consequences of development policies and political choices (Wilhite, 2000).

Charlotte Benson and Edward Clay (Wilhite, 2000), despite the difficulty mentioned above, made the attempt of assessing the economic impacts of recurrent and prolonged droughts on Sub-Saharan African countries. The assessment consisted of using regression analysis to find a correlation between drought time series and sectoral economic growth in six countries, including Burkina Faso and Senegal, which are located in the Sahel region. Using the importance of dry and irrigated agriculture, the level of water use, the gross domestic product per capita (GDP), and the availability of natural resources as criteria, they defined four categories of economies.

- ✓ The "*Simple economies*," represented by countries such as Burkina Faso, are characterized by a subsistence dry agriculture, a weak structure, low gross domestic product (GDP), none or limited integration between agricultural and modern sectors, and a mainly rural population. For this category in which most countries of the Sahel fall into, rural economy is most sensitive to drought impacts, and due to the absence of intersectoral integration, the multiplier effect of drought impacts on other economic sectors is insignificant. Therefore, the return of normal rainfall can be enough to prompt an immediate rehabilitation of this economy category;
- ✓ The "*Intermediate economies*", category is represented by countries including Senegal and characterized by a high diversification and intersectoral integration, a dependency on labor-intensive and low technology manufacturing, and income from export of local renewable natural resources, import of equipment and inputs. For those economies, drought has adverse effects on all sectors through the multiplier effect; the recovery in agriculture following the return of normal rainfall does not result in the automatic rehabilitation of the intermediate economy as a whole.
- ✓ The "*Complex economies*" are relatively developed economies with little dependency on agriculture and other water related activities; none of the study countries qualifies for having a complex economy. Nevertheless, for this economic category, drought shock is limited in terms of impacts on the economy.

- ✓ The "*Dualistic economies*" are represented by Zambia and South Africa, and are largely dependant on mainly export-oriented activities of extractive minerals, which coexist with a low productive rural sector; the two sectors are not fully integrated. When necessary investments for water supply to the extractive sector are made, drought shocks are limited to agriculture with no significant multiplier effects on the rest of the economy.

According to the authors, the positive correlation between the level of economic development and the vulnerability to drought shocks is consistent with the "*Inverted U*" theory of economic development. In other words, while drought shocks are increasingly severe on the economy during the early stages of economic development, they subside progressively at later stages.

### **2.3.2.3. Environmental impacts**

As direct consequences of the severe drought impacts, the weak resource base of the Sahelian environment has been subjected to an overexploitation that may have initiated or exacerbated the current processes of soil erosion and vegetation destruction (Ariel Dinar et al., 2000; World Bank, 1985.)

According to researchers, droughts and environmental degradation are the primary factors at play in the desertification, which is taking place in the Sahel, especially around cities (World Bank, 1985). In extension, the desertification of marginal lands adjacent to the Sahara desert is resulting in what is known as the southward extension of the Sahara desert.

#### **2.3.2.4. Social impacts**

Depending on the characteristics of drought (severity, duration and spatial extent), and preexisting economic conditions, the welfare of affected people may be at risk. As Wilhite (2000) defined the risk for a specific area to sustain adverse effects of drought is the product of the potential for the hazard to happen and the vulnerability of exposed people. In the case of the Sahel region, the increasing vulnerability of almost all countries to drought impacts may result from their weak economic structure (Benson and Clay, 2000), the chronic poverty, the limited resources base.

#### **2.3.3. Drought-responses in the Sahel region**

In extension of the emergency relief responses to the drought episodes of the 1970s and 1980s, the governments of the region took different initiatives at national and regional levels in order to minimize the risk for future events (CCD/UNSO, 1999.)

##### **2.3.3.1. National policies and strategies**

Mali, after getting its independence, defined its objectives for water resources development in the basins of the Senegal and Niger Rivers. The initial objectives were to meet water demands for irrigation and power generation, which resulted in the expansion of the "*Office du Niger*" and the construction of a limited number of water control infrastructures.

However, at the inception of drought in the early 1970s, emergency interventions for providing food relief and water supply services were given first priority. The ensuing responses were aimed at achieving long-term goals of food security and water supply. The implementation of different projects resulted in a better assessment of water resources. The assessment provided the basis for defining the guidelines for the development of water resources. The "*Schema de Mise en Valeur des Ressources en Eau du Mali*" (DNHE, 1990), except for the long-term goals implied for drought impacts management did stated specific objectives and strategies of drought impacts management. The recent document "*Rapport National sur la vision Nationale de l'eau a l'horizon 2025*" seems not to fill in the gap.

Mali has started to implement the provisions of the UN-CCD by defining and adopting its PNAE/PAN-CID in 1998. Like the other documents mentioned previously, the PNAE/PAN-CID seems not to have procedures applicable to the tactical and emergency management of drought impacts.

#### **2.3.2.5. Regional coordination**

On regional scale, the need for coordinating drought mitigation efforts led to the creation of the "Permanent Inter-state Committee to combat drought in the Sahel" (CILSS.) The CILSS, with the strategic objective of a comprehensive development of the Sahel region, has put its focus on the rural sector (Somerville, 1986.) In support of this regional initiative,

member-countries of the OCDE have created "Club du Sahel" as a channel to provide the CILSS with financial resources.

There are basin-scale organizations for both the Niger River and Senegal Rivers.

### **2.3.2.6. International cooperation**

The United Nations established the Sudano-Sahel Office (UNSO) for coordinating its interventions in the Sahel region. The office evolved and became the UN Office to Combat Desertification (UN-CCD) with the mission of helping concerned countries define their National Action Programs (NAPs) and implementation strategies.

The UN-CCD and the OFDA (The Office of Foreign Disaster Assistance, USAID), in order to define their support priorities for drought impacts management, co-sponsored a comprehensive assessment of the status of drought preparedness and management in African countries (Wilhite, 1999.) The assessment has shown that drought preparedness remains an objective to attain in almost all African countries. Among other deficiencies, the assessment has identified the lack of a planning process and resources. Therefore, a ten-step planning framework was recommended for drought impact management in African countries; the framework is very similar to what was initially developed for drought impacts management planning in the USA.

## **Chapter 3: THE NIGER RIVER IN MALI: DROUGHT CHARACTERISTICS AND SUSTAINABILITY OF THE SYSTEM**

### **3.1. INTRODUCTION**

This research has developed a methodology for drought impact management, which is applicable to different stages or levels of severity of a drought event. This requires that the user have knowledge of the characteristics of droughts in a particular river basin or location. Obviously, the strategies applied to manage drought impacts will be different if a drought lasts only one or two years as opposed to droughts lasting for many years. This will also be true for a less severe drought in terms of water supply deficit. For this research study, the flow regime of the Niger River and its tributary of the Bani River are analyzed to determine drought characteristics in terms of flow deficits at selected gaging stations. The selected gaging stations are:

- ✓ Koulikoro, Mali on the Niger River mainstream;
- ✓ Douna, Mali on the Bani River;
- ✓ Mopti, Mali on the Niger River;
- ✓ Dire, Mali on the Issa-Ber, which drains part of the waters of the inner delta where the Bani River discharges into the Niger.

As reviewed in chapter 2, for assessing the status of water or moisture availability, different variables have been used to develop aggregate indices. However, in many instances, and especially in developing countries, the data

for variables such as rainfall, discharge, soil moisture, reservoir level, and evapotranspiration may not be available or reliable. Therefore, assessing drought characteristics based upon limited or unreliable data of water or moisture may lead to incorrect conclusions. Often the most complete data set may be the river discharge at selected sites. As shown by Salas et al (1990), river discharge may be used to characterize drought.

In this study, drought characteristics for the Niger River are assessed in terms of deficits in three measures of discharge. For all the selected gaging stations, the data of monthly discharges was available. They were used to generate the annual minimum, mean and maximum flows. The long-term average values of the annual minimum flows, annual mean flows and the annual maximum flows were computed to serve as references or threshold levels. The decision to use the long-term average values as reference levels was based on the assumption that, with limited water control, the demands will not be allowed to go beyond the average values.

These three threshold variables were selected to help characterize the response of the river to changes in the rainfall and land-use regimes in the basin. Traore Z. (1998) has shown that the Niger River and the Bani River have sustained large deficits in their discharges for a period of approximately 30 years, which indicates a greater potential for drought in the basin (Figure 3.1-1.) By the run theory, drought may be characterized in terms of volume

of flow deficit, duration or cumulative flow deficits, which can be generated in each flow type by using their threshold values.

The annual average minimum flow threshold is used to provide insight about how the baseflow may be impacted during drought. For example, changes in land-use in the basin might adversely impact the recharge of aquifers and their supplies to the baseflow in the river. Drought impacts are most severe during low flow periods, and therefore, changes in the minimum flow characteristics of the river may be very important in planning drought impact management activities. The annual average maximum flow threshold is used to provide insight about how the maximum flows may be changing. With limited water control, changes in flood flows may affect the potential for navigation and flood plain activities, such as, agriculture and fishing.

Statistics of drought characteristics were computed for the flow deficits resulting from these three threshold levels. Probability distribution functions were also fitted to the same data of flow deficits. This information was then integrated and the sustainability index of river discharge was determined. The sustainability index is ultimately used to determine the priority order of the management objectives that are considered in the multi-criteria decision analysis of drought impact management strategies.

To complete the picture, flow statistical analysis was performed at each gaging stations; the results are presented in the Appendix.

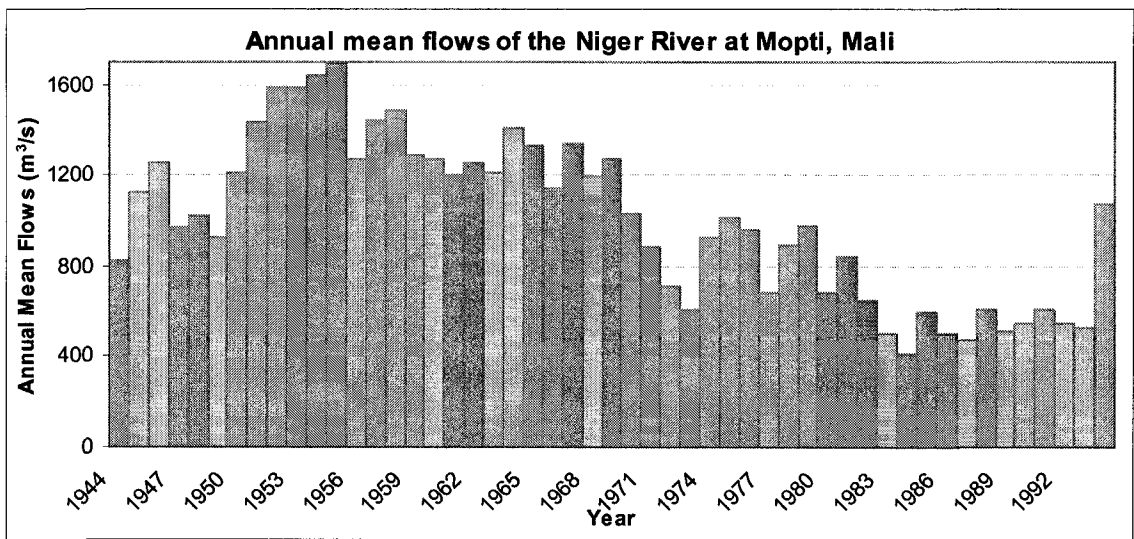
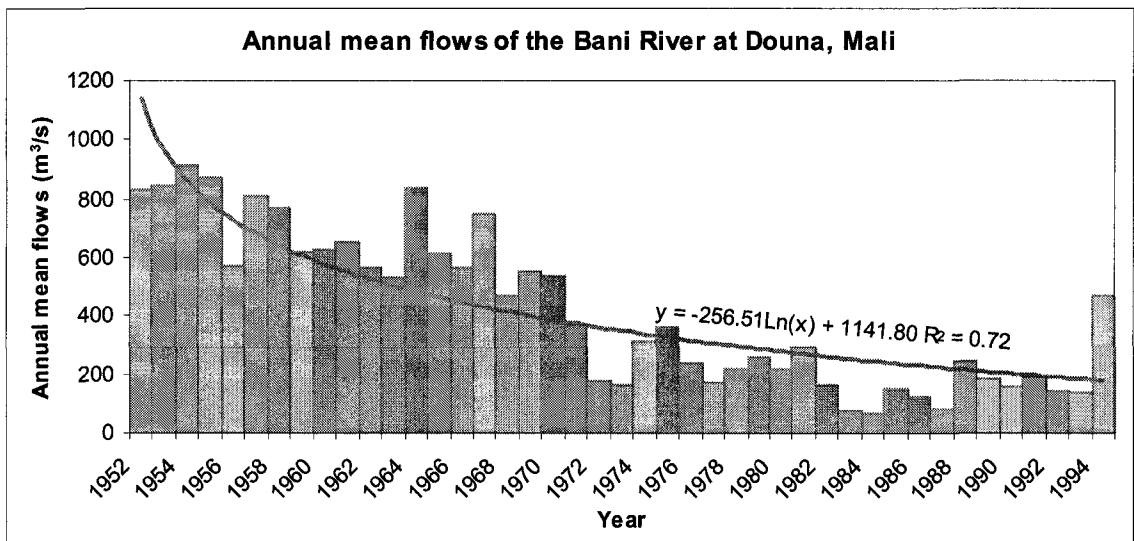
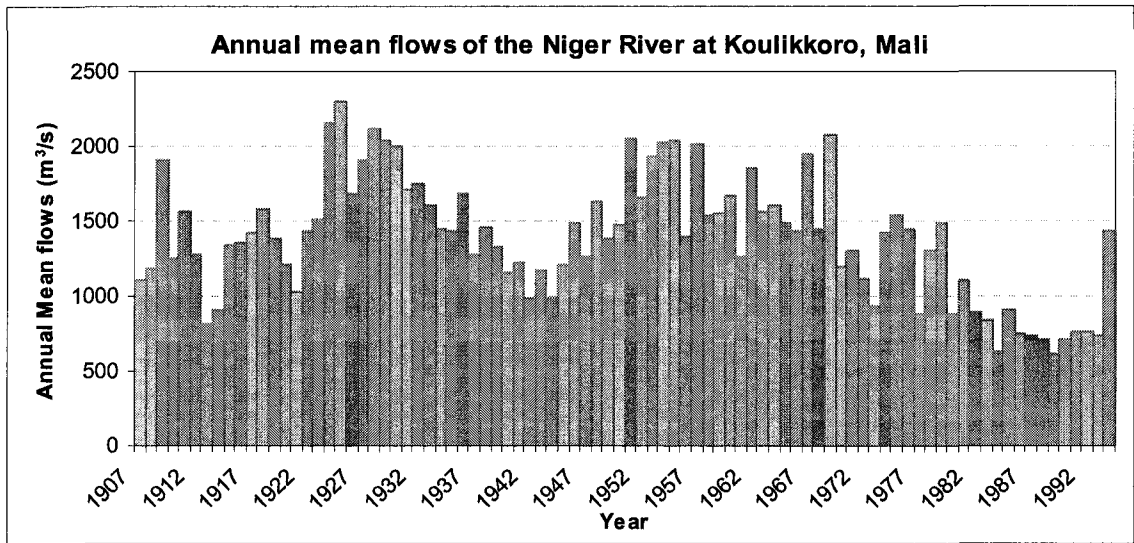


Figure 3.1-1: Annual mean flows of the Niger and Bani Rivers

### 3.2. METHODOLOGY

For each of the selected stations, the threshold values of annual minimum flow mean flows and maximum flows were computed as the long-term average values. Using the run theory, annual flow deficits or excesses are then computed as the difference between the threshold values and actual annual values of the minimum flow, average flow and maximum flow:

$$\text{Deficit or Excess} = (X_i - \bar{X}) \text{ (Equation 3.2-1)}$$

Where:

$X_i$  is the actual value of the variable (annual minimum, mean or maximum flows);

$\bar{X}$  is the long-term average value of the variable under consideration.

To make the deficits or excesses of different flow types easier to compare, they were expressed in terms of the ratio (percentage) of the threshold values. This ratio, also termed intensity of the deficits, is computed as:

$$\text{Ratio or Intensity (\%)} \text{ of deficits} = \frac{X_i - \bar{X}_i}{\bar{X}_i} \text{ (Equation 3.2-2)}$$

With the flow deficit data, drought impacts are analyzed in terms of deficits in individual annual flows, cumulative volume of deficits over the period of a drought and duration of deficits or run lengths of drought periods. To analyze the cumulative probability distribution of the deficits, the Weibull plotting position formula (McCuen R., 1998) is used to compute the non-exceedance

probability of the empirical Cumulative Distribution Function (CDF) expressed as:

$$P(X_n \leq X) = \frac{n}{N+1} \text{ (Equation 3.2-3)}$$

Where:

- ✓  $X_n$  is the  $n^{\text{th}}$  actual value of the deficit in the annual minimum discharge;
- ✓  $n$  is the rank of  $X_n$  in the ordered data:  $n = 1 \dots N$ ;
- ✓  $X$  is the random variable, which may be annual minimum discharge, annual mean discharge or annual maximum discharge;
- ✓  $N$  is the total length of the time series.

Since the focus of drought study is on the deficits, all flow excesses were considered zero deficits. This assumes that water demand will not exceed the average annual flow, since this condition would never be sustainable. Based on the statistical characteristics of the computed deficits, a probability distribution function was selected to fit the time-series.

As evidenced by the frequent occurrence of deficits in the three flow types at the different gaging stations, the recurrent and persistent decreases in rainfall of the last three decades have had serious impacts on the flow regime of the Niger and the Bani Rivers. Without infrastructure to control and store water, the potential for flows to sustain deficits is a major source of uncertainty and risk for the different water uses relying on them. Therefore,

it may be necessary to assess the sustainability of the three types of flows at the different gaging stations.

The method of weighted statistical indices (ASCE, 1998) was applied to the generated deficit data. The method consists of using the statistics of reliability, resilience, and vulnerability as performance indicators for measuring sustainability. These performance indicators are defined as follows (ASCE, 1998):

- ✓ Reliability = Number of satisfactory (no deficit) values/Total number of values recorded or generated;
- ✓ Resilience = Number of times a satisfactory value follows an unsatisfactory measure/total number of unsatisfactory values;
- ✓ Vulnerability = Conditional exceedence probability of flow deficit.

The Sustainability Index = [Reliability]\*[Resilience]\*[Vulnerability].

For an alternative option and a set of criteria, the overall sustainability may be obtained by summing up the sustainability indices obtained for each criterion.

These formulas are applied to the deficit data generated from the annual minimum, mean, and maximum flows. The data include the single-year flow deficits, the cumulative deficits, and the run lengths of deficit.

### **3.3. THE NIGER RIVER SYSTEM IN MALI**

The Niger River is 4200 Km long, and is made of numerous streams, which, for the most part, originate in the Futa Jallon high mountain of Guinea. In its 1700 km course across Mali, the Niger River receives water from the Sankarani right after entering into Mali. It then flows northeastward and gets water from its right bank tributary of the Bani River just before forming a large inland delta where it divides up into a series of braided distributaries. After exiting the inner delta, the Niger River forms a bend, which marks the northern limit of its course and the contact with the Sahara desert. From the bend, the Niger River flows across the Niger Republic and Nigeria where it discharges its waters into the Atlantic Ocean. In Mali, the basin of the Niger River may be divided as follows (J. Rodier, 1964):

- ✓ *The Upper basin of the Niger River* consists of the watershed upstream of Koulikoro for the mainstream and Mopti for the Bani River. From Guinea, the estimate of the average total annual discharge of the Niger River is 40 km<sup>3</sup> (FAO, 1997). In this part of this upper basin, the main aquifers are poor water-bearing Granitic and metamorphic formations of the basement and sedimentary sandstones. Water wells tapping those aquifers have a success rate of 62-80% for the basement and 55-80% for the sedimentary; the wells have an average yield ranging from 4.8 to 5.4 m<sup>3</sup>/h and 4.6 to 8.8 m<sup>3</sup>/h respectively (La Synthese Hydrologique du Mali, DNHE, 1990). The limited capacity of the aquifers does not provide a significant water supply to sustain the baseflow, which means a high reliance of

the flow regime on runoff. At the outlet of the upper basin, the Niger River and the Bani River are discharging an average annual water volume of 70 km<sup>3</sup> into the inner delta.

- ✓ *The inner delta* is the long reach of the Niger River stretching from Koulikoro (Niger River proper) and Mopti for the Bani River to Timbuktu. In the inner delta, waters from the main stream and the Bani River flow through a series of braided channels, which during flood periods, overflow and supply water to large floodplains and lakes on the two riverbanks. During wet years, the total area of the flooded plains and lakes may reach up to 30000 km<sup>2</sup>. Of the 70 km<sup>3</sup> annual volume of water discharged into the inner delta, about 30 km<sup>3</sup> are lost to evapotranspiration and seepage. During the extreme wet year of 1969 and dry year of 1973, the volumes of water lost to the inner delta were 46 km<sup>3</sup> and 17 km<sup>3</sup> respectively (DNHE, 1990). According to Francisco Olivera et al. (1995), water is lost at the rate of 1.711 m<sup>3</sup>/s/km for the inner delta compared to 0.171 m<sup>3</sup>/s/km for the rest of the Niger River. During periods of low flows, part of the floodwater lost in the inner delta may return to the river through different channels. Therefore, throughout the inner delta, the seasonal flow variation is less pronounced than it is upstream and downstream. In the inner delta, the aquifers consist of sandy deposits of alluviums, which may be tapped by shallow wells with high productivity. Because of the low velocity of the flow in this almost flat area, most of the sediment the Niger River transports from upstream is deposited in the

inner delta. At the exit of the inner delta, the average annual discharge of the Niger River is about 35 m<sup>3</sup>/s.

- ✓ *The middle Niger system:* After exiting the inner delta, the Niger River keeps its northeastward course in a well-defined channel before engaging in a southeastward bend, which is commonly known as the "Niger Loop" (FAO, 1997). In this reach, the Niger River does not receive significant water contributions.

Water control infrastructure on the Niger River in its course in Mali is limited.

There are two existing dams and one projected:

- ✓ The Selingue dam and Reservoir with a storage capacity of 2X10<sup>9</sup> m<sup>3</sup>;
- ✓ The Markala diversion dam without storage capacity;
- ✓ The projected dam and reservoir of Taoussa with a storage capacity of 3X10<sup>9</sup> m<sup>3</sup>;

Even the Taoussa project is implemented the combined storage capacity will be only 5X10<sup>9</sup> m<sup>3</sup>, which is less than 20% of the 108X10<sup>9</sup> m<sup>3</sup> total annual discharge of the Niger River in this area.

### **3.3.1. Niger River at Koulikoro, Mali**

The location of the city of Koulikoro, Mali is considered the downstream end of the upper basin of the Niger River. Its gaging station has the longest of all historical flow data records to be used in this study.

As already mentioned, the long-term average values of the annual minimum, mean, and maximum flows serve as thresholds. For the Niger River at

Koulikoro gaging station, these threshold values are 65.13 m<sup>3</sup>/s for the minimum flows, 1384.85 m<sup>3</sup>/s for the annual mean flows, and 4926.93 m<sup>3</sup>/s for the annual maximum flows.

### **3.3.1.1. Characteristics of flow deficits**

The graphs of Figure 3.3.1.1-1 and Figure 3.3.1.1-2 show the periods of deficits or excesses in each of the three flow types. For the selected threshold values, Figure 3.3.1.1-1 shows the values of deficits or excesses volumes in the discharges and figure 3.3.1.1-2 shows them in terms of ratio of the threshold value. From these graphs, similar trends are observed in the periods of occurrence of deficits in the different flow types. That is, in general, the occurrence of sequences of deficits appears to coincide for the minimum, average and maximum flows. There are exceptions to this, however. Notice that for the period beginning in the early 1980s there are sequences of deficits in the annual mean and maximum flows, yet this is a period of excess for the minimum flows. The appearance of excesses in the annual minimum flows after 1981 is most likely due to the releases at Selingue reservoir. This exception illustrates why three thresholds, instead of an average flow threshold only, were considered in this study.

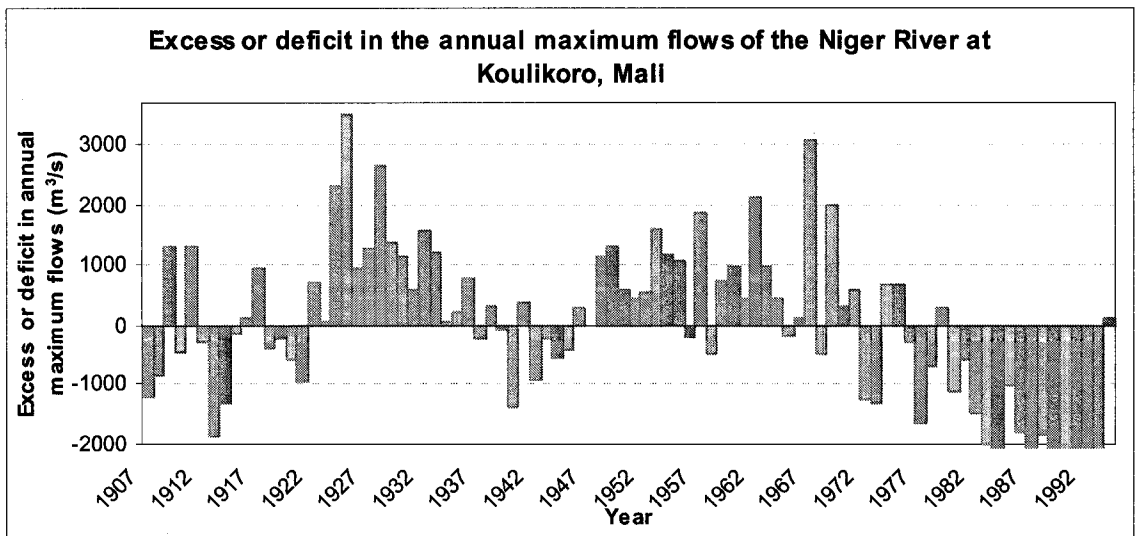
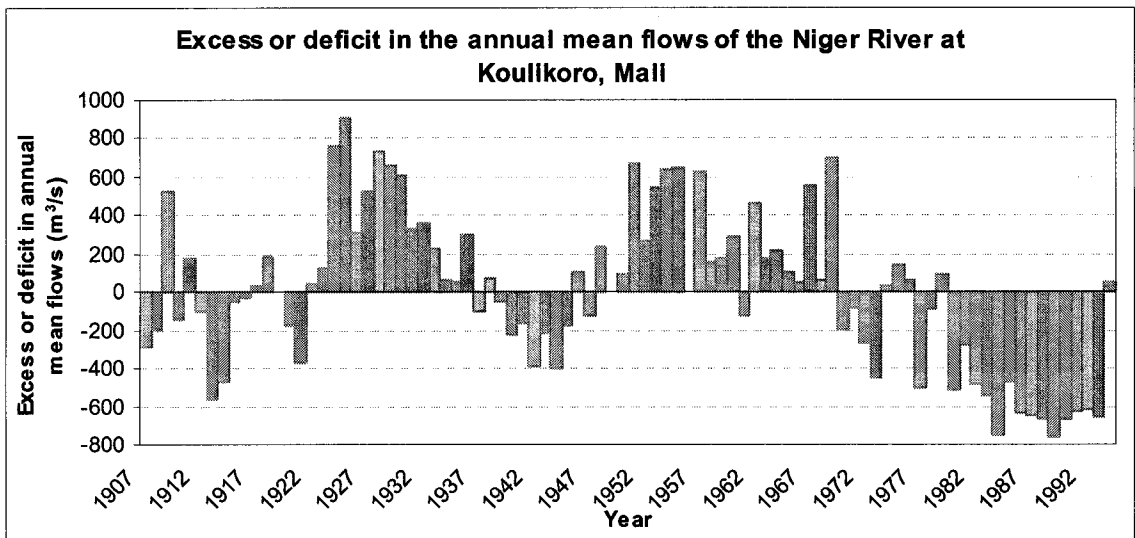
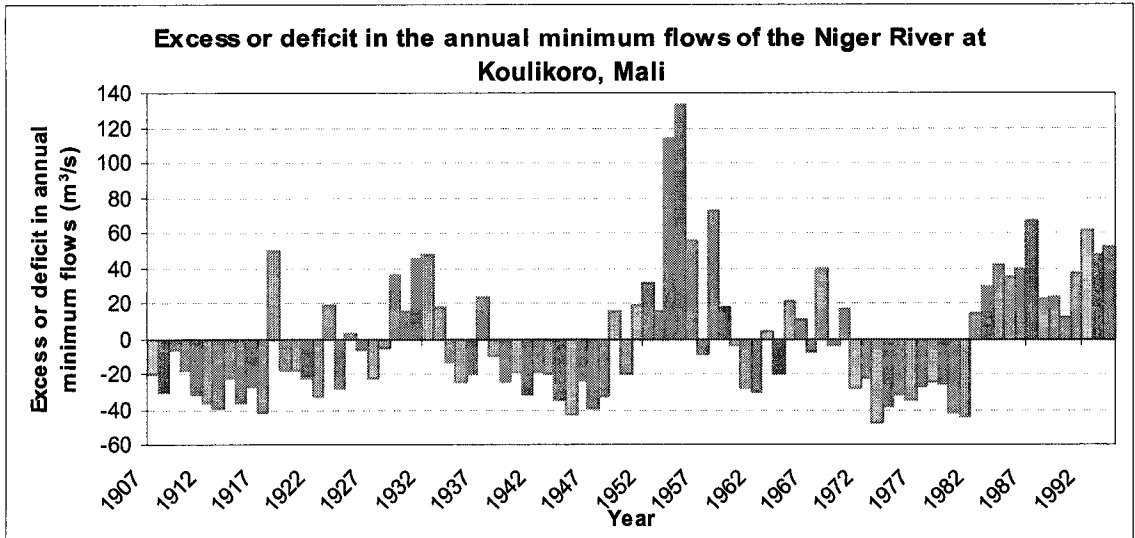


Figure 3.3.1.1-1: Flow excess or deficits of the Niger River at Koulikoro

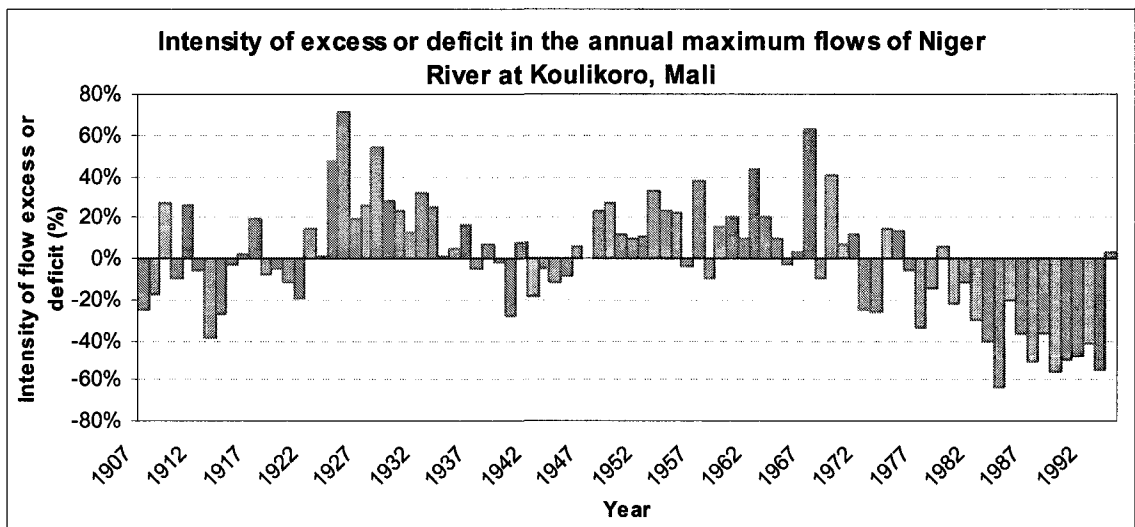
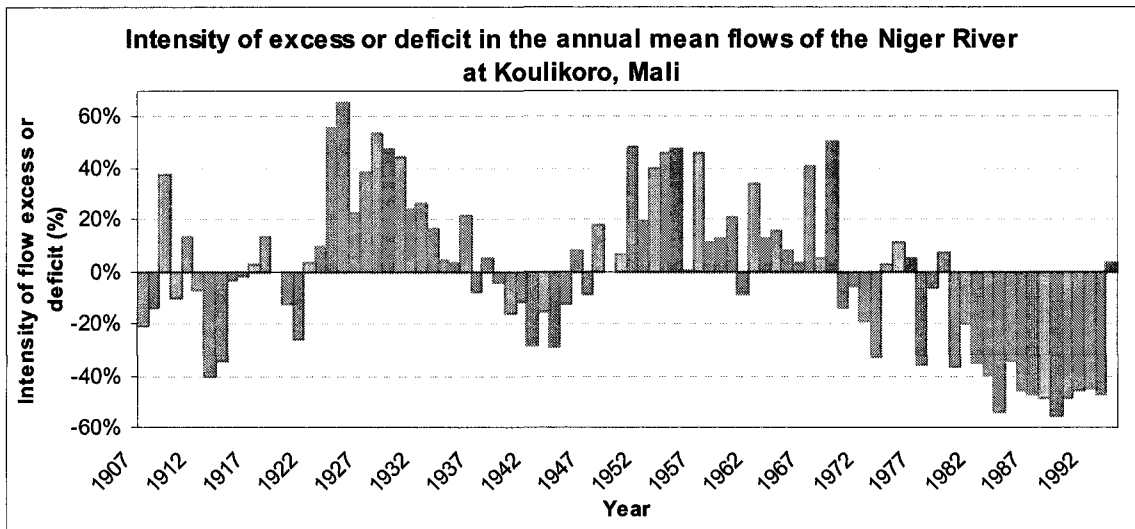
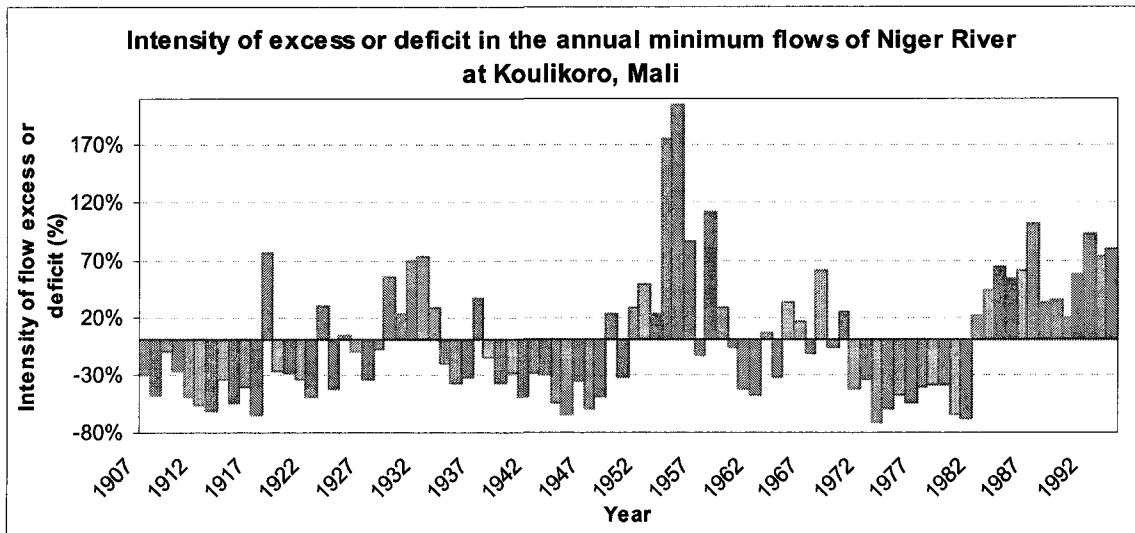


Figure 3.3.1.1-2: Intensity of flow excess or deficit of the Niger River at Koulikoro

For the average minimum flow threshold, three main sequences of flow deficits are evident. The lengths of the sequences are slightly in excess of 10 years, indicating that drought in this section of the basin can be persistent for at least a decade. Figure 3.3.1.1-2 also shows that the intensity of the flow deficits can be quite large. The annual minimum discharges sustained deficits up to 72% of the threshold value; the deficits in the annual mean discharges were as large as 55%, and the deficits in the annual maximum flows went up to 63%. The deficits in the three types of annual flows were used to generate the histogram shown in Figure 3.3.1.1-3, below. Note that years with excess were considered as zero deficit years.

Next, the runs of periods of deficits or excesses were analyzed. For deficits only, this information is summarized in table 3.3.1.1-1; the table shows the years corresponding to the runs of deficits, the duration of the run in years, the average value of annual deficit intensity and the maximum value of intensity that occurred during the run. These values of intensity are illustrated in Figure 3.3.1.1-2.

For each individual run, the cumulative deficits and run length were calculated and used to create the histograms shown in figure 3.3.1.1-4 and Figure 3.3.1.1-5.

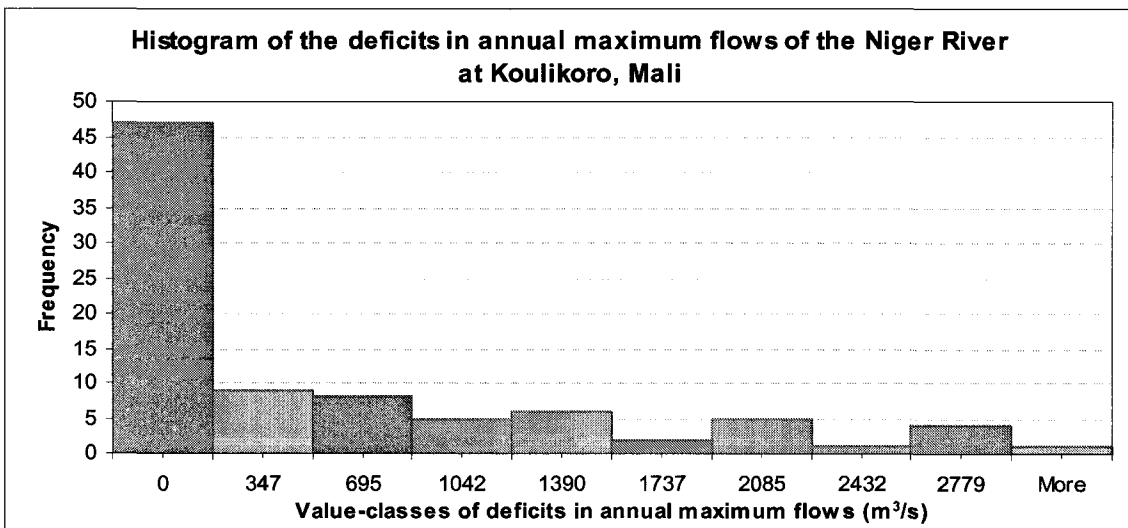
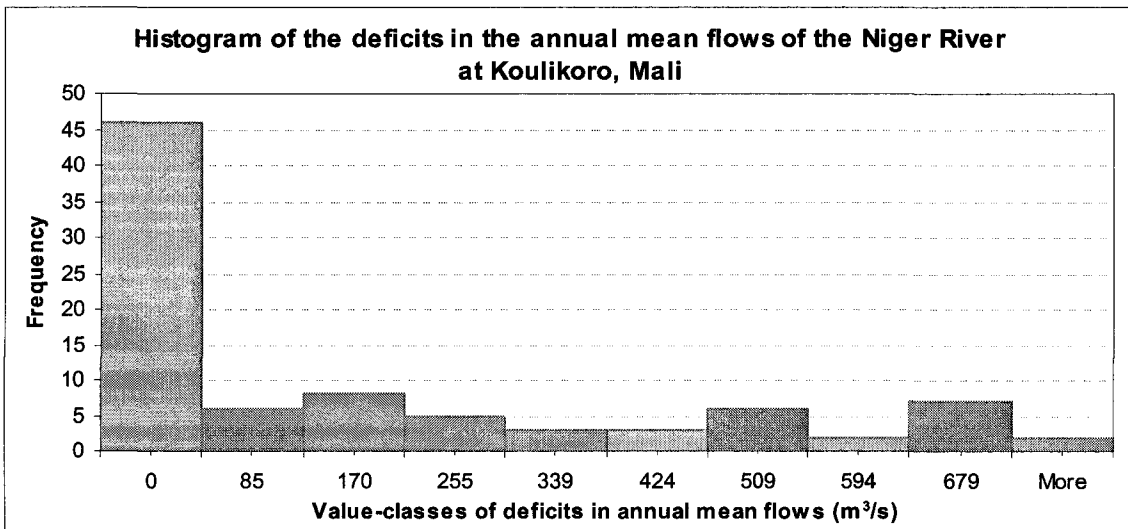
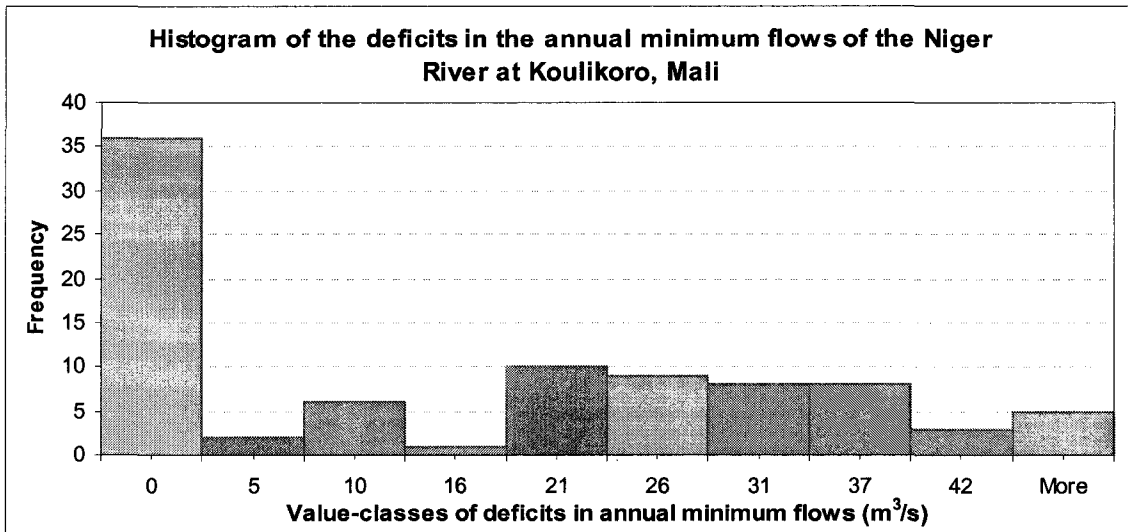


Figure 3.3.1.1-3: Histograms of flow deficits of the Niger River at Koulikoro, Mali

Discharge Type	Deficits sequence	Start (Year)	End (Year)	Run length (Year)	Intensity of the deficits (%)	
					Average	Maximum
Annual minimum Flow	1	1907	1917	11	43	65
	2	1919	1922	4	34	50
	3	1924	1924	1	43	43
	4	1926	1928	3	17	33
	5	1934	1936	3	30	38
	6	1938	1948	11	41	65
	7	1950	1950	1	32	32
	8	1957	1957	1	13	13
	9	1960	1962	3	45	47
	10	1964	1964	1	31	31
	11	1971	1981	11	51	72
<b>Maximum</b>				<b>11</b>	<b>51%</b>	<b>72%</b>
Average annual mean flow	1	1907	1908	2	17	20
	2	1910	1910	1	10	10
	3	1912	1916	5	17	41
	4	1919	1921	3	13	26
	5	1937	1937	1	8	8
	6	1939	1945	7	17	29
	7	1947	1947	1	9	9
	8	1961	1961	1	8	8
	9	1970	1973	4	18	33
	10	1977	1978	2	21	37
	11	1980	1993	14	43	55
<b>Maximum</b>				<b>14</b>	<b>43%</b>	<b>55%</b>
Annual maximum flow	1	1907	1908	2	21	25
	2	1910	1910	1	9	9
	3	1912	1915	4	19	38
	4	1918	1921	4	11	19
	5	1937	1937	1	5	5
	6	1939	1940	2	15	28
	7	1942	1945	4	11	18
	8	1956	1956	1	4	4
	9	1958	1958	1	10	10
	10	1965	1965	1	3	3
	11	1968	1968	1	10	10
	12	1972	1973	2	26	26
	13	1976	1978	3	18	33
	14	1980	1993	14	40	63
<b>Maximum</b>				<b>14</b>	<b>40%</b>	<b>63%</b>

Table 3.3.1.1-1: Intensity of the deficits in the discharges of the Niger River at Koulikoro, Mali

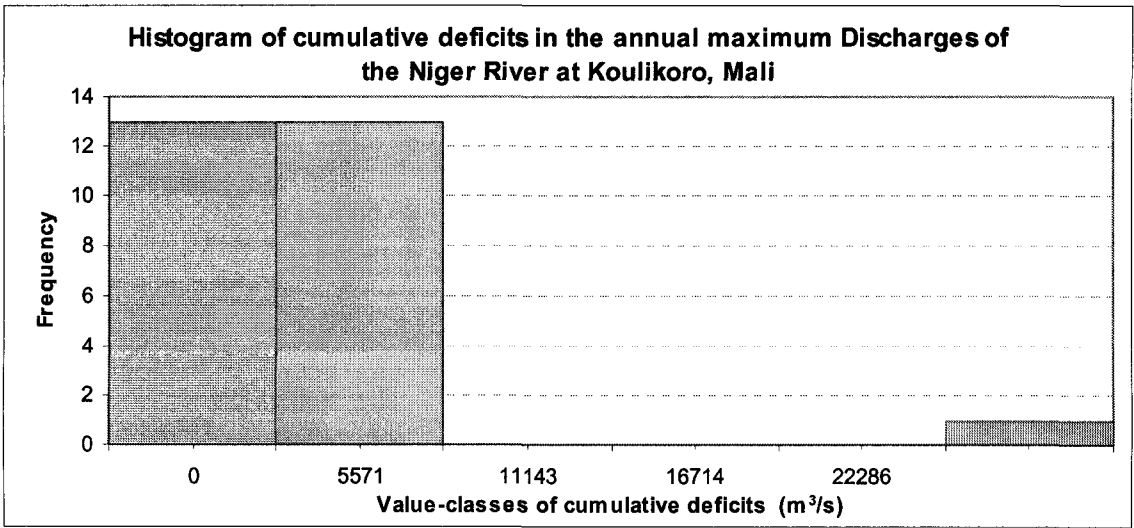
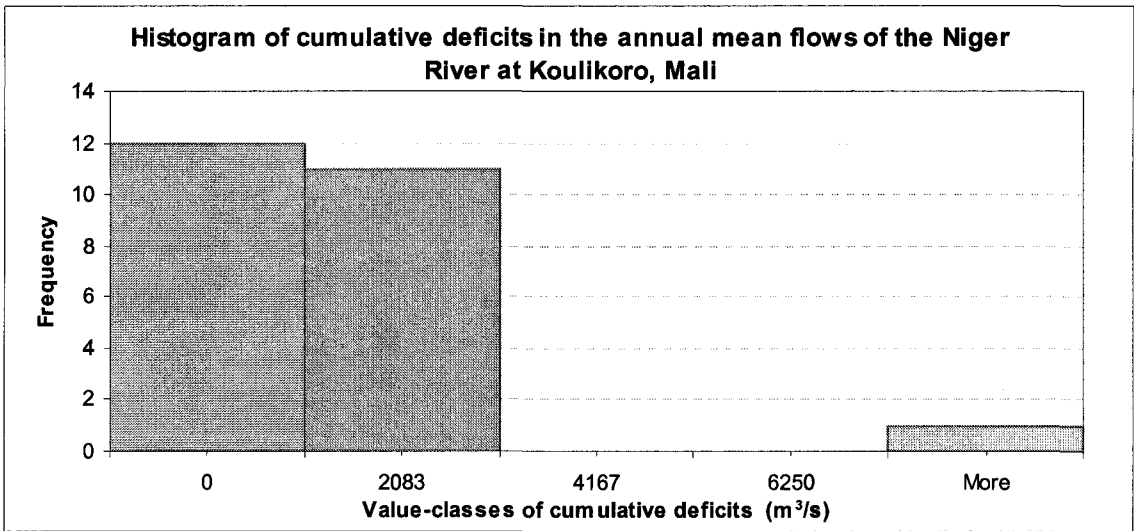
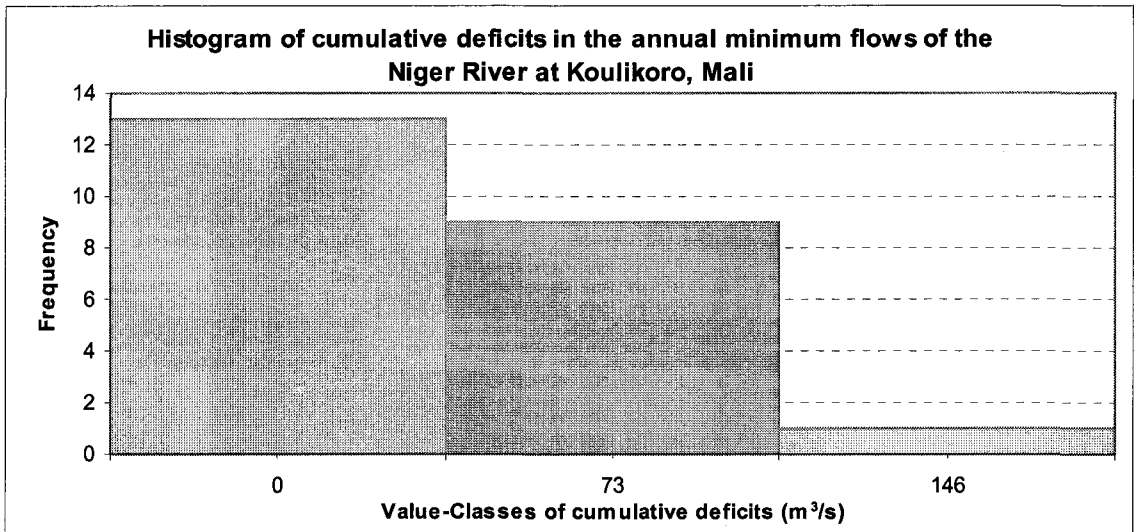


Figure 3.3.1.1-4: Histograms of cumulative flow deficits of the Niger River at Koulikoro, Mali

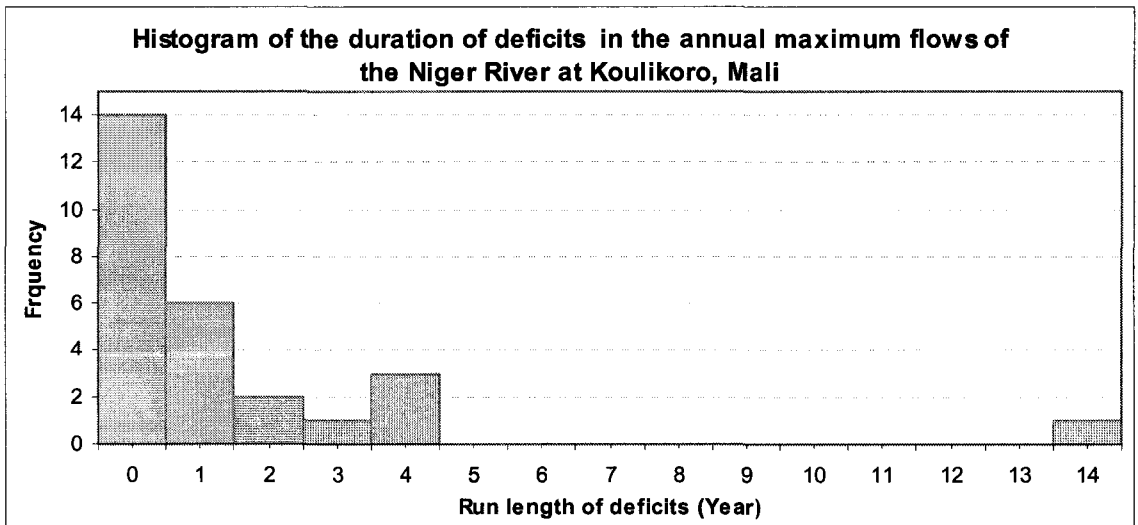
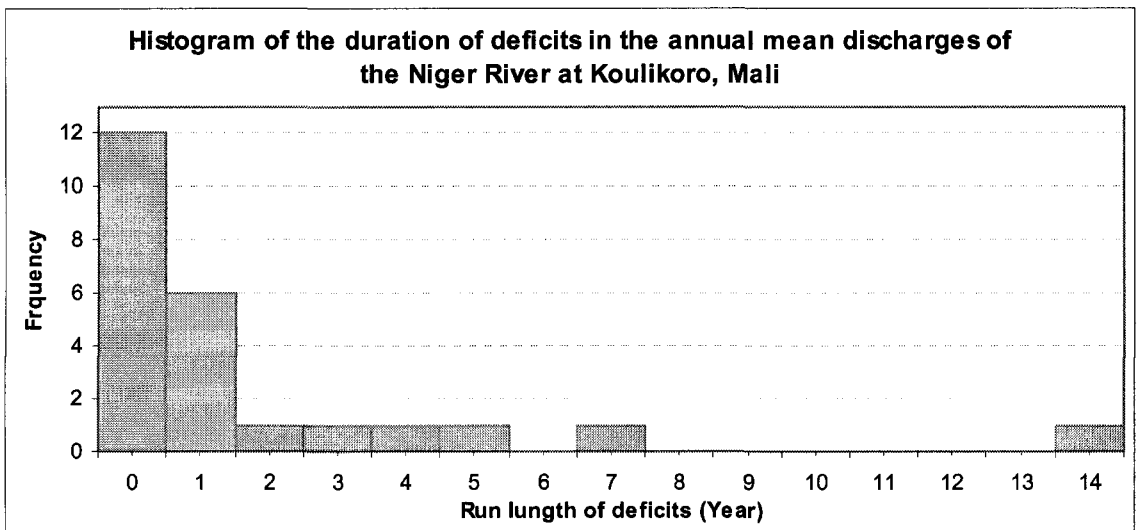
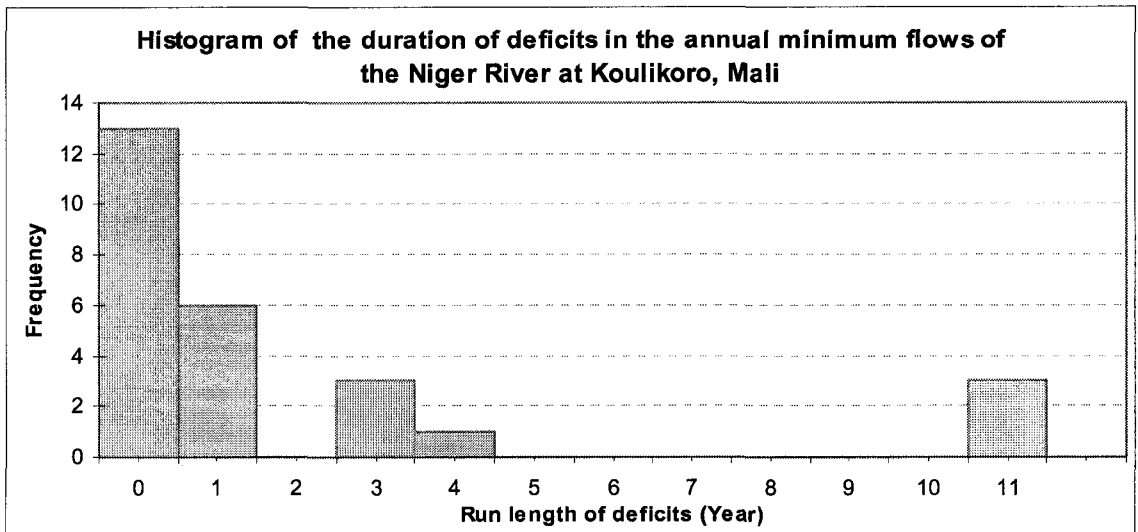


Figure 3.3.1.1-5: Histograms of the duration of deficits in the flows of the Niger River at Koulikoro, Mali

### 3.3.1.2. Statistics and distribution of the deficits, cumulative deficits and run lengths

The statistics of the different deficit data are given in Table 3.3.1.2-1.

<b>Statistics</b>	<b>Deficits in annual flows</b>		
	Minimum discharge	Mean Discharge	Maximum Discharge
Mean	14.8	161.70	528.46
Standard Error	1.61	25.06	86.73
Median	11.58	0	0
Standard Deviation	15.07	235.04	813.55
Sample Variance	227.00	55245.66	661869.90
Kurtosis	-1.23	0.11	1.44
Skewness	0.44	1.25	1.57
Coefficient of variation	1.02	1.45	154
Range	46.93	763.52	3126.93
Minimum	0	0	0
Maximum	46.93	763.52	3126.93
	<b>Cumulative deficits</b>		
Mean	50.08	592.88	1660.86
Standard Error	20.35	348.32	990.65
Median	2.1148	1.13	78.47
Standard Deviation	103.77	1706.41	5242.04
Sample Variance	10768.28	2911831.85	27479017.97
Kurtosis	4.55	20.49	25.50
Skewness	2.39	4.41	4.96
Coefficient of variation	2.07	2.88	3.16
Range	365.83	8333.15	27857.05
Minimum	0	0.00	0.00
Maximum	365.83	8333.15	27857.05
	<b>Run length</b>		
Mean	2	1.71	1.46
Standard Error	0.69	0.65	0.53
Median	0.50	0.50	0.5
Standard Deviation	3.51	3.20	2.80
Sample Variance	12.32	10.22	7.81
Kurtosis	3.28	9.48	15.50
Skewness	2.09	2.90	3.61
Coefficient of variation	1.75	1.87	1.91
Range	11	14	14
Minimum	0	0	0
Maximum	11	14	14

Table 3.3.1.2-1: Statistics of the deficits in annual flows of the Niger River at Koulikoro

The Weibull plotting position formula was used to estimate the CDFs of the deficit data. To increase the ease of estimating return periods, selected probability distributions functions were also fitted to the data and compared to the empirical estimate provided by the plotting position formula.

The beta distribution was fitted to the annual minimum flow data; the probability density function (PDF) is formulated as:

$$f(X; \alpha, \beta, A, B) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha) \cdot \Gamma(\beta)} \left( \frac{X - A}{B - A} \right)^{\alpha-1} \left( \frac{B - X}{B - A} \right)^{\beta-1} \quad (\text{Equation 3.3.1.2-1})$$

Where:

- ✓  $\alpha$  is the scale parameter;
- ✓  $\beta$  is the shape parameter;
- ✓  $A$  is the lower bound of the variation range of the variable annual minimum flow deficit, which in this case is zero;
- ✓  $B$  is the upper bound of the variation range of the variable
- ✓ The gamma function is:  $\Gamma(\alpha) = \int_0^{\infty} X^{\alpha-1} e^{-X} dX$  (Equation 3.3.1.2-2);
- ✓  $X$  is the variable (deficits.)

The parameters of the Beta function may be estimated by the method of moments as follows:

$$\hat{\alpha} = \hat{\mu}^2 \frac{(1 - \hat{\mu})}{\hat{\delta}^2} - \hat{\mu} \quad (\text{Equation 3.3.1.2-3})$$

$$\hat{\beta} = \hat{\alpha} \frac{(1 - \hat{\mu})}{\hat{\mu}} \quad (\text{Equation 3.3.1.2-4})$$

Where:

- ✓  $\hat{\mu}$  is the mean of the sample;

- ✓  $\hat{\delta}$  is the standard deviation of the sample;

The initial moment estimators of the parameters were optimized by least square method.

The gamma probability distribution was fitted to the data of deficits in the annual mean and maximum discharges. The gamma probability density function (PDF) of the cumulative deficit is described by:

$$f(X; \alpha, \beta) = \frac{1}{\alpha^\beta \Gamma(\beta)} X^{\beta-1} e^{-X/\alpha} \text{ (Equation 3.3.1.2-5)}$$

Where:

- ✓  $\alpha$  is the scale parameter;
- ✓  $\beta$  is the shape parameter;
- ✓  $\Gamma(\beta)$  is the gamma function as defined previously;
- ✓  $X$  is the variable (deficits.)

The parameters may be estimated by the method of moment as follows:

- ✓  $\hat{\alpha} = \frac{\hat{\mu}}{\hat{\beta}}$  (Equation 3.3.1.2-6);
- ✓  $\hat{\beta} = \left( \frac{\hat{\mu}}{\hat{\sigma}} \right)^2$  (Equation 3.3.1.2-7);

Where:

- ✓  $\hat{\mu}$  is the mean of the sample;
- ✓  $\hat{\sigma}$  is the standard deviation of the sample;

Fitted probability function		Deficits in annual		
		Minimum discharge	Mean Discharge	Maximum Discharge
Type		Beta	Gamma	Gamma
Parameters Estimators	$\hat{\alpha} =$	0.39	0.42	161.70
	$\hat{\beta} =$	0.77	1252.46	235.04
Coefficient of determination		0.95	0.95	0.99
		Cumulative deficits		
Type		Gamma	Gamma	Gamma
Parameters Estimators	$\hat{\alpha} =$	0.23	0.12	0.10
	$\hat{\beta} =$	215.01	4911.30	16545.01
Coefficient of determination		0.99	0.98	0.95
		Run length of deficits		
Type		Gamma	Gamma	Gamma
Parameters Estimators	$\hat{\alpha} =$	0.32	0.29	0.27
	$\hat{\beta} =$	6.16	5.98	5.34
Coefficient of determination		0.98	0.96	0.97

Table 3.3.1.2-2: Parameters of probability distribution functions fitted to the deficits in the annual flows of the Niger River at Koulikoro

Order	Volume of deficits in Annual Discharge (m <sup>3</sup> /s)			Return Period of deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of deficits in			CDF of Fitted Distribution to deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Beta	Annual Mean flows: Gamma	Annual Maximum flows: Gamma
1	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
2	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
3	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
4	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
5	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
6	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
7	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
8	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
9	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
10	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
11	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
12	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
13	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
14	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
15	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
16	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
17	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
18	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
19	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
20	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
21	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
22	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
23	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
24	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
25	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
26	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
27	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
28	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
29	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
30	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
31	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
32	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
33	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
34	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
35	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
36	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0.00	0.00	0.00
37	4.23	0.00	0.00	1.71	1.01	1.01	0.42	0.01	0.01	0.34	0.00	0.00
38	4.33	0.00	0.00	1.75	1.01	1.01	0.43	0.01	0.01	0.34	0.00	0.00
39	5.53	0.00	0.00	1.78	1.01	1.01	0.44	0.01	0.01	0.38	0.00	0.00
40	5.73	0.00	0.00	1.82	1.01	1.01	0.45	0.01	0.01	0.39	0.00	0.00
41	6.53	0.00	0.00	1.85	1.01	1.01	0.46	0.01	0.01	0.41	0.00	0.00
42	7.93	0.00	0.00	1.89	1.01	1.01	0.47	0.01	0.01	0.44	0.00	0.00
43	8.23	0.00	0.00	1.93	1.01	1.01	0.48	0.01	0.01	0.45	0.00	0.00
44	10.13	0.00	0.00	1.98	1.01	1.01	0.49	0.01	0.01	0.49	0.00	0.00

Table 3.3.1.2-3: Probability distributions and return periods of the deficits in the annual flows of the Niger River at Koulikoro, Mali

Order	Volume of deficits in Annual Discharge (m <sup>3</sup> /s)			Return Period of deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of deficits in			CDF of Fitted Distribution to deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Beta	Annual Mean flows: Gamma	Annual Maximum flows: Gamma
45	13.03	0.00	0.00	2.02	1.01	1.01	0.51	0.01	0.01	0.54	0.00	0.00
46	17.23	0.00	0.00	2.07	1.01	1.01	0.52	0.01	0.01	0.61	0.00	0.00
47	17.43	1.04	0.00	2.12	2.12	1.01	0.53	0.53	0.01	0.61	0.07	0.00
48	18.03	2.25	76.93	2.17	2.17	2.17	0.54	0.54	0.54	0.62	0.10	0.34
49	18.43	23.50	136.93	2.23	2.23	2.23	0.55	0.55	0.55	0.62	0.31	0.43
50	19.03	45.07	156.93	2.28	2.28	2.28	0.56	0.56	0.56	0.63	0.42	0.45
51	19.83	51.27	186.93	2.34	2.34	2.34	0.57	0.57	0.57	0.64	0.44	0.48
52	20.13	80.69	226.93	2.41	2.41	2.41	0.58	0.58	0.58	0.65	0.53	0.52
53	20.43	87.33	246.93	2.47	2.47	2.47	0.60	0.60	0.60	0.65	0.55	0.54
54	20.53	102.55	246.93	2.54	2.54	2.47	0.61	0.61	0.60	0.65	0.58	0.54
55	20.53	105.67	286.93	2.54	2.62	2.62	0.61	0.62	0.62	0.65	0.59	0.57
56	21.73	116.22	306.93	2.70	2.70	2.70	0.63	0.63	0.63	0.67	0.61	0.58
57	21.83	119.53	386.93	2.78	2.78	2.78	0.64	0.64	0.64	0.67	0.62	0.63
58	22.13	140.43	426.93	2.87	2.87	2.87	0.65	0.65	0.65	0.67	0.65	0.65
59	22.33	161.52	466.93	2.97	2.97	2.97	0.66	0.66	0.66	0.68	0.69	0.67
60	23.23	168.47	476.93	3.07	3.07	3.07	0.67	0.67	0.67	0.69	0.70	0.67
61	24.23	172.88	486.93	3.18	3.18	3.18	0.69	0.69	0.69	0.70	0.70	0.68
62	24.63	193.02	566.93	3.30	3.30	3.30	0.70	0.70	0.70	0.71	0.73	0.71
63	25.03	194.29	576.93	3.42	3.42	3.42	0.71	0.71	0.71	0.71	0.73	0.72
64	25.23	212.90	586.93	3.56	3.56	3.56	0.72	0.72	0.72	0.71	0.75	0.72
65	26.33	226.13	696.93	3.71	3.71	3.71	0.73	0.73	0.73	0.73	0.76	0.76
66	26.73	263.43	846.93	3.87	3.87	3.87	0.74	0.74	0.74	0.73	0.80	0.80
67	27.73	277.10	906.93	4.05	4.05	4.05	0.75	0.75	0.75	0.75	0.81	0.81
68	27.83	283.57	946.93	4.24	4.24	4.24	0.76	0.76	0.76	0.75	0.81	0.82
69	27.93	364.31	1006.93	4.45	4.45	4.45	0.78	0.78	0.78	0.75	0.87	0.83
70	30.43	393.09	1106.93	4.68	4.68	4.68	0.79	0.79	0.79	0.78	0.88	0.85
71	30.43	396.84	1216.93	4.68	4.94	4.94	0.79	0.80	0.80	0.78	0.88	0.87
72	31.03	455.25	1256.93	5.24	5.24	5.24	0.81	0.81	0.81	0.79	0.90	0.87
73	31.73	474.25	1296.93	5.56	5.56	5.56	0.82	0.82	0.82	0.79	0.91	0.88
74	31.83	474.30	1326.93	5.93	5.93	5.93	0.83	0.83	0.83	0.80	0.91	0.88
75	32.13	485.15	1366.93	6.36	6.36	6.36	0.84	0.84	0.84	0.80	0.91	0.89
76	32.33	496.86	1486.93	6.85	6.85	6.85	0.85	0.85	0.85	0.80	0.92	0.90
77	35.13	508.68	1646.93	7.42	7.42	7.42	0.87	0.87	0.87	0.83	0.92	0.92
78	35.23	547.62	1806.93	8.09	8.09	8.09	0.88	0.88	0.88	0.84	0.93	0.93
79	35.63	563.72	1826.93	8.90	8.90	8.90	0.89	0.89	0.89	0.84	0.94	0.93
80	36.43	617.60	1876.93	9.89	9.89	9.89	0.90	0.90	0.90	0.85	0.95	0.93
81	38.83	627.52	2006.93	11.13	11.13	11.13	0.91	0.91	0.91	0.88	0.95	0.94
82	39.23	636.35	2056.93	12.71	12.71	12.71	0.92	0.92	0.92	0.88	0.95	0.94
83	39.43	650.60	2386.93	14.83	14.83	14.83	0.93	0.93	0.93	0.89	0.95	0.96
84	42.03	651.19	2466.93	17.80	17.80	17.80	0.94	0.94	0.94	0.92	0.95	0.96
85	42.13	670.70	2536.93	22.25	22.25	22.25	0.96	0.96	0.96	0.92	0.96	0.97
86	42.53	671.36	2716.93	29.67	29.67	29.67	0.97	0.97	0.97	0.93	0.96	0.97
87	44.53	751.44	2736.93	44.50	44.50	44.50	0.98	0.98	0.98	0.95	0.97	0.97
88	46.93	763.52	3126.93	89.00	89.00	89.00	0.99	0.99	0.99	1.00	0.97	0.98

Table 3.3.1.2-3 (continued): Non-exceedance probabilities and return periods of the deficits in the annual flows

Order	Volume of deficits cumulative deficit in Discharge (m <sup>3</sup> /s)			Return Period of cumulative deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of cumulative deficits in			CDF of Fitted Distribution to cumulative deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Gamma	Annual Mean flows: Gamma	Annual Maximum flows: Gamma
1	0.00	0	0.00	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0	0.00
2	0.00	0	0.00	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
3	0.00	0	0.00	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
4	0.00	0	0.00	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
5	0.00	0	0.00	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
6	0.00	0	0.00	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
7	0.00	0	0.00	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
8	0.00	0	0.00	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
9	0.00	0	0.00	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
10	0.00	0	0.00	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
11	0.00	0	0.00	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
12	0.00	0	0.00	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
13	0.00	2.25	0.00	1.04	2.08	1.04	0.04	0.52	0.03	0.00	0.42	0.00
14	4.23	105.67	0.00	2.08	2.08	1.04	0.52	0.56	0.03	0.44	0.67	0.00
15	7.93	116.22	156.93	2.25	2.08	2.07	0.56	0.60	0.52	0.51	0.67	0.66
16	8.23	119.53	186.93	2.45	2.08	2.23	0.59	0.64	0.52	0.51	0.68	0.67
17	20.43	140.43	226.93	2.70	2.08	2.42	0.63	0.68	0.52	0.62	0.69	0.68
18	20.53	477.86	466.93	3.00	2.08	2.64	0.67	0.72	0.52	0.62	0.79	0.73
19	27.93	533.82	476.93	3.38	4.17	2.90	0.70	0.76	0.52	0.67	0.80	0.73
20	32.99	584.19	486.93	3.86	5.00	3.22	0.74	0.80	0.52	0.69	0.81	0.74
21	58.19	992.39	1443.86	4.50	6.25	3.63	0.78	0.84	0.72	0.77	0.86	0.82
22	62.49	1209.10	2063.86	5.40	8.33	4.14	0.81	0.88	0.72	0.78	0.87	0.84
23	89.42	1614.62	2147.73	6.75	12.50	4.83	0.85	0.92	0.72	0.83	0.90	0.85
24	295.93	8333.15	2157.73	9.00	25.00	5.80	0.89	0.96	0.83	0.96	0.99	0.85
25	308.03		2553.86	13.50		7.25	0.93		0.86	0.97		0.86
26	365.83		2630.80	27.00		9.67	0.96		0.86	0.98		0.86
27			3647.73			14.50			0.86		0.98	0.89
28			27857.05			29.00			0.97			0.99
Coefficient of determination R <sup>2</sup> =										0.98		0.97

Table 3.3.2.1.2-4: Probability distributions of the cumulative deficits in the annual flows

Order	Duration of deficits in Discharge (m <sup>3</sup> /s)			Return Period of duration of deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of the duration of deficits in			CDF of Fitted Distribution to the duration of deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Gamma	Annual Mean flows: Gamma	Annual Maximum flows: Gamma
1	0	0	0	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
2	0	0	0	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
3	0	0	0	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
4	0	0	0	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
5	0	0	0	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
6	0	0	0	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
7	0	0	0	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
8	0	0	0	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
9	0	0	0	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
10	0	0	0	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
11	0	0	0	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
12	0	0	0	1.04	1.04	1.04	0.04	0.04	0.03	0.00	0.00	0.00
13	0	1	0	1.04	2.08	1.04	0.04	0.52	0.03	0.00	0.64	0.00
14	1	1	0	2.08	2.08	1.04	0.52	0.52	0.03	0.60	0.64	0.00
15	1	1	1	2.08	2.08	2.07	0.52	0.52	0.52	0.60	0.64	0.67
16	1	1	1	2.08	2.08	2.07	0.52	0.52	0.52	0.60	0.64	0.67
17	1	1	1	2.08	2.08	2.07	0.52	0.52	0.52	0.60	0.64	0.67
18	1	1	1	2.08	2.08	2.07	0.52	0.52	0.52	0.60	0.64	0.67
19	1	2	1	2.08	4.17	2.07	0.52	0.76	0.52	0.60	0.76	0.67
20	3	3	1	3.86	5.00	2.07	0.74	0.80	0.52	0.79	0.82	0.67
21	3	4	2	3.86	6.25	3.63	0.74	0.84	0.72	0.79	0.87	0.79
22	3	5	2	3.86	8.33	3.63	0.74	0.88	0.72	0.79	0.90	0.79
23	4	7	2	6.75	12.50	3.63	0.85	0.92	0.72	0.84	0.94	0.79
24	11	14	3	9.00	25.00	5.80	0.89	0.96	0.83	0.97	0.99	0.85
25	11		4	9.00		7.25	0.89		0.86	0.97		0.89
26	11		4	9.00		7.25	0.89		0.86	0.97		0.89
27			4			7.25			0.86			0.89
28			14			29.00			0.97			0.99
Coefficient of determination $R^2 =$										0.97		0.95

Table 3.3.1.2-5: Probability distributions of the run lengths of deficits in the annual flows

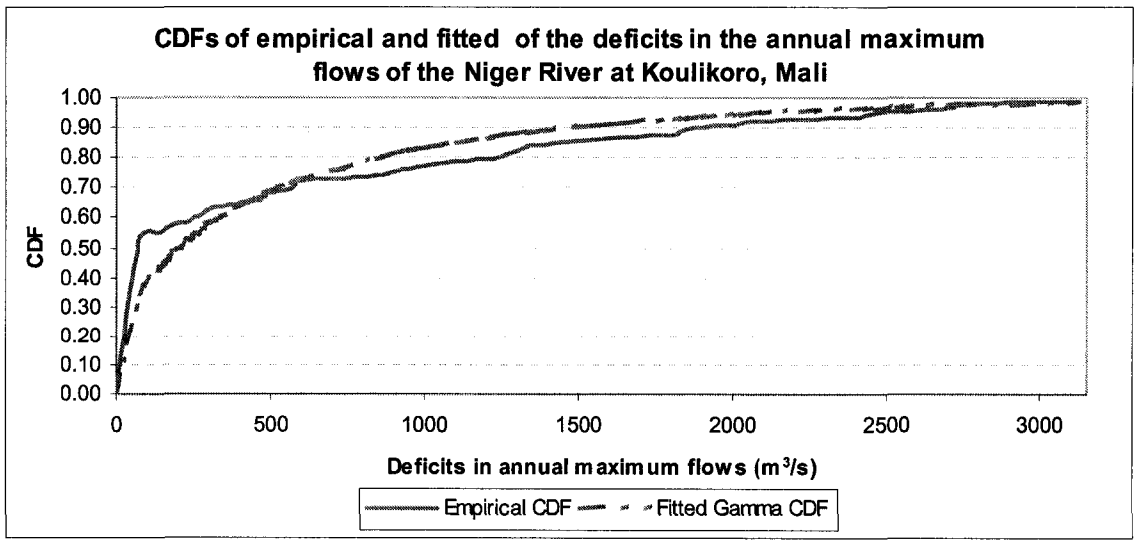
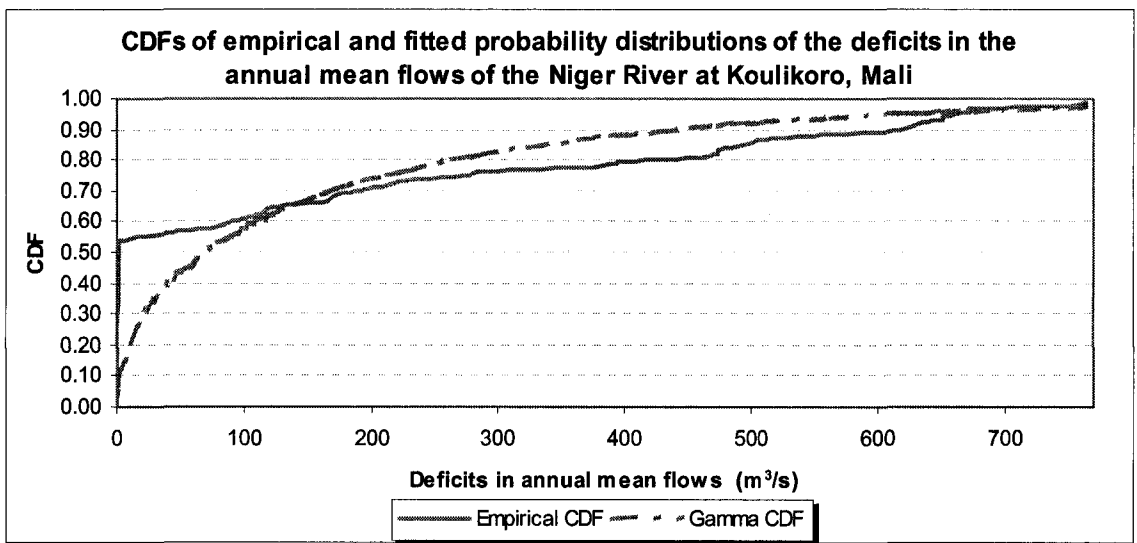
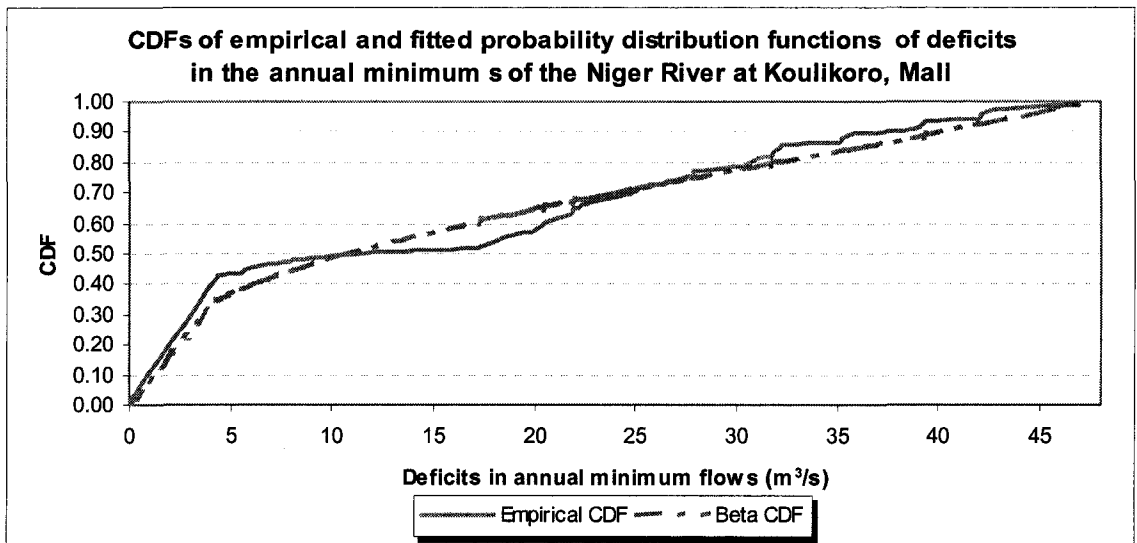


Figure 3.3.1.2-1: CDFs of probability distribution functions of flow deficits

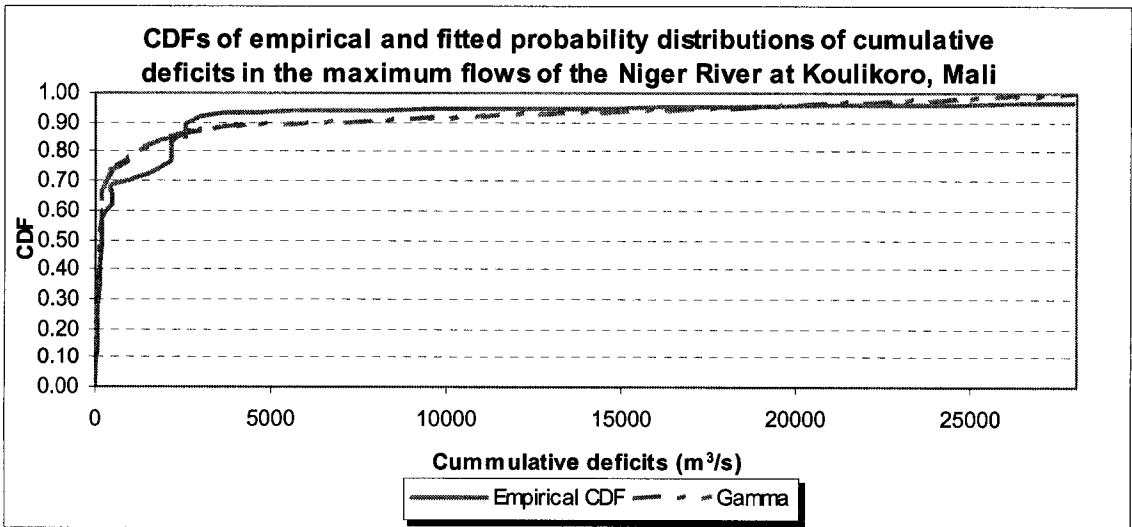
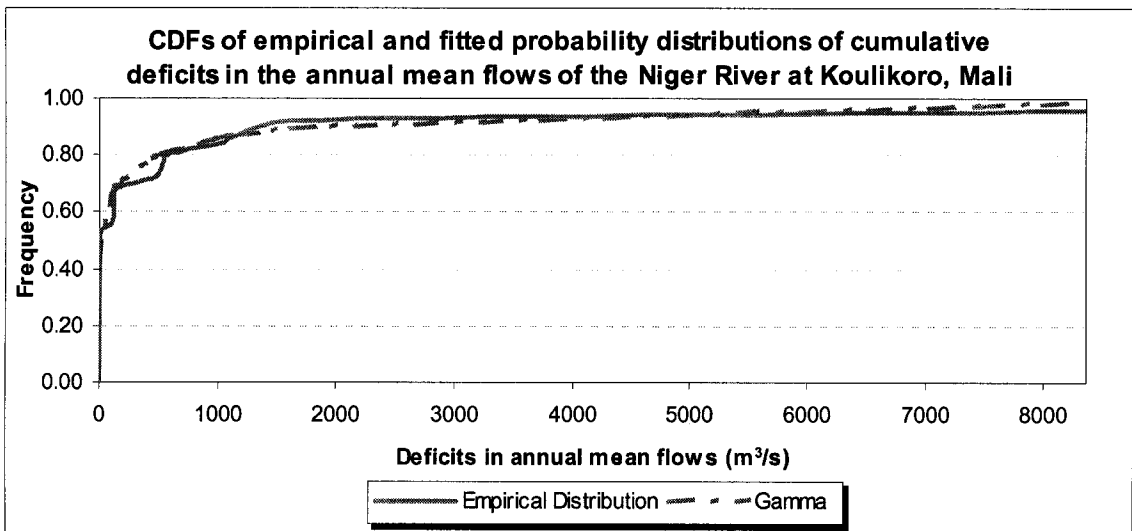
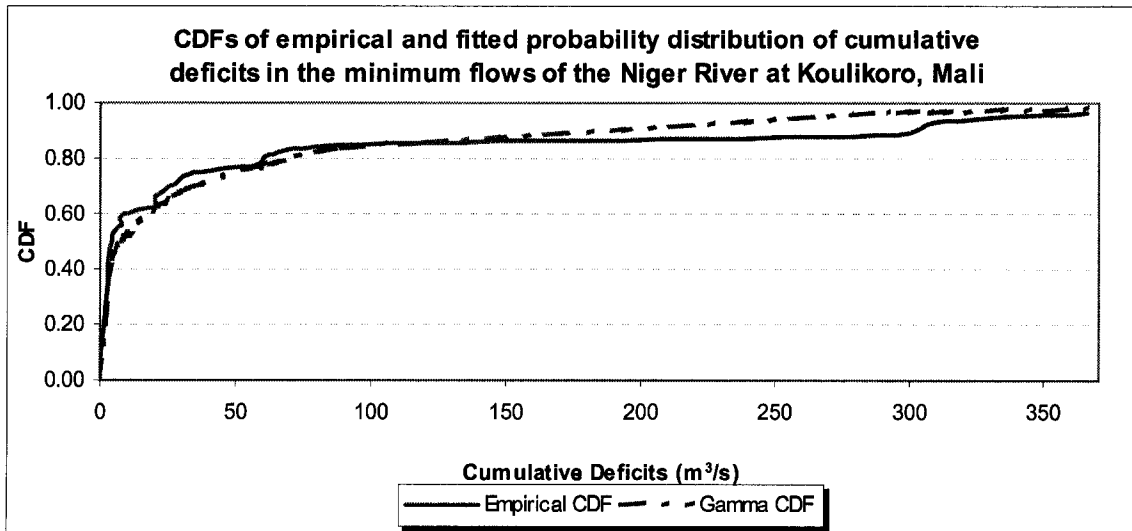


Figure 3.3.1.2-2: CDFs of probability distribution functions of flow cumulative deficits

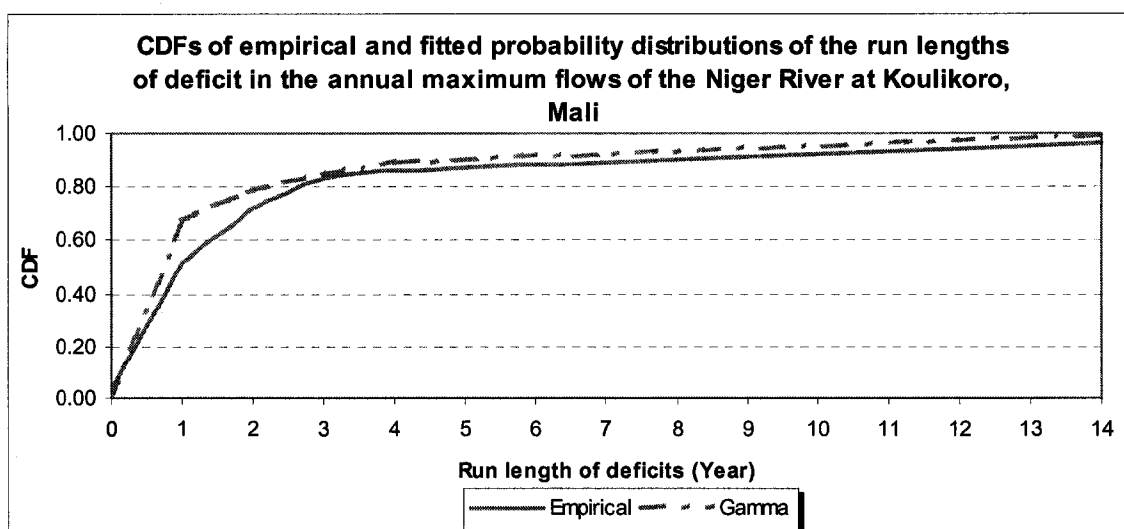
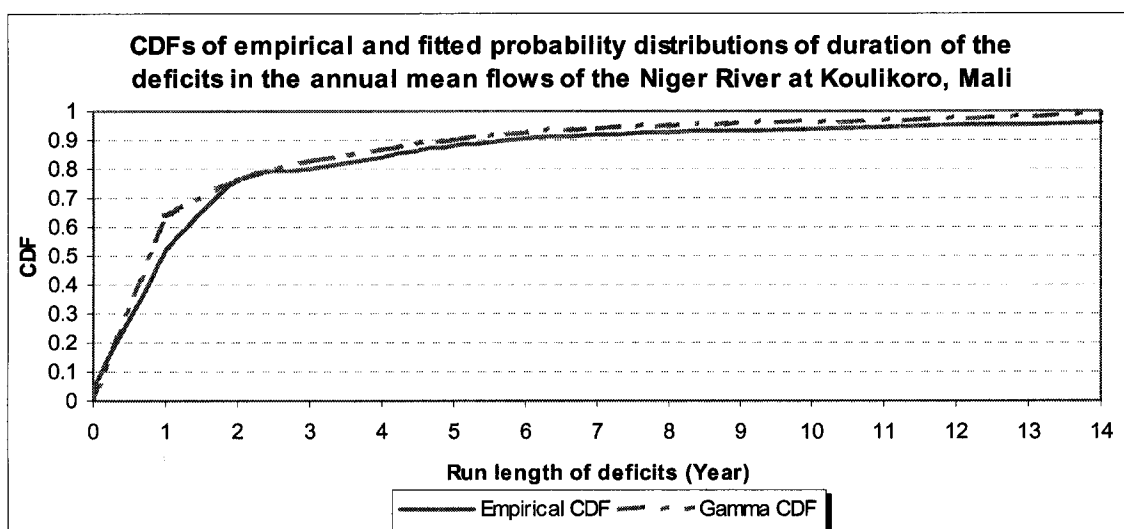
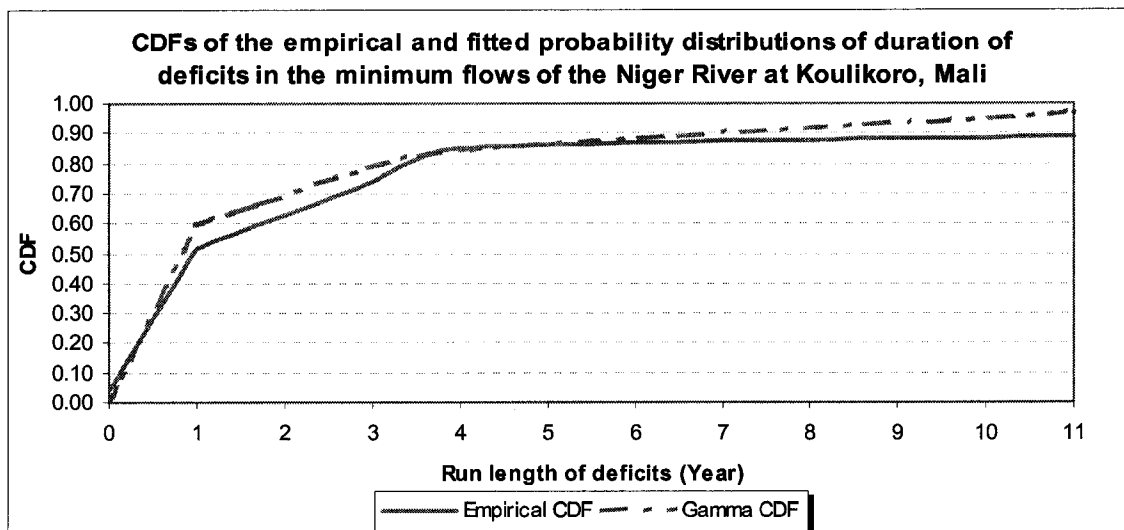


Figure 3.3.1.2-3: CDFs of probability distributions of the run length of deficit in the flows of the Niger River at Koulikoro

### 3.3.1.3. Sustainability of annual flows

As introduced earlier, the method of weighted statistical indices was applied to the deficits data in order to assess the sustainability of the annual minimum, mean, and maximum flows for single-year deficits, cumulative deficits, and durations of deficits. The vulnerability values given in table 3.3.1.3-1 are those obtained for the only expected values of the deficits; those of table 3.3.1.3-2 are for the potential levels of single-year flow deficits. Table 3.3.1.3-3 provides the ranking of the three flow types based on their sustainability indices.

<b>Drought Impacts on Discharges</b>	<b>Performance Indicator</b>	<b>Annual Minimum Discharges</b>	<b>Annual Mean Discharges</b>	<b>Annual Maximum Discharges</b>
<b>Single Year Deficits</b>	Reliability	36/88 = 0.41	46/88 = 0.52	47/88 = 0.53
	Resilience	13/52 = 0.25	12/42 = 0.29	14/41 = 0.34
	Expected Deficit (m <sup>3</sup> /)	1302.14/52 = 25.04	14228.19/42 = 347.03	46504.20/41 = 1134.25
	Vulnerability (Expected)	25/52 = 0.48	20/42 = 0.48	18/41 = 0.44
	Sustainability	0.049	0.071	0.080
<b>Cumulative Deficits</b>	Reliability	13/26 = 0.5	12/24 = 0.5	14/28 = 0.5
	Resilience	13/13 = 1	12/12 = 1	14/14 = 1
	Expected Deficit (m <sup>3</sup> /)	1302.14/13 = 100.16	14229.23/12 = 1016.37	46504.20/14 = 3321.73
	Expected Vulnerability	3/13 = 0.23	4/14 = 0.29	2/14 = 0.14
	Sustainability	0.12	0.14	0.07
<b>Deficits Duration</b>	Reliability	13/26 = 0.5	12/24 = 0.5	14/28 = 0.5
	Resilience	13/13 = 1	12/12 = 1	14/14 = 1
	Expected Duration	52/13 = 4	41/12 = 3.42	41/14 = 2.93
	Expected Vulnerability	3/13 = 0.23	4/12 = 0.33	5/14 = 0.29
	Sustainability	0.12	0.17	0.14
<b>Sustainability</b>		<b>0.280</b>	<b>0.381</b>	<b>0.294</b>

Table 3.3.1.3-1: Flow Sustainability Indices for the expected values of flow deficits and duration of deficit in the flows of the Niger River at Koulikoro, Mali.

Deficit in Annual Discharge (m <sup>3</sup> /s)			Vulnerability (Exceedence Probability)			Reliability			Resilience			Sustainability Index		
Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
4.23			0.98									0.101		
4.33			0.96									0.099		
5.53			0.94									0.097		
5.73			0.92									0.095		
6.53			0.90									0.093		
7.93			0.88									0.091		
8.23			0.87									0.089		
10.13			0.85									0.087		
13.03			0.83									0.085		
17.23			0.81									0.083		
17.43	1.04		0.79	0.98								0.081	0.147	
18.03	2.25	76.93	0.77	0.95	0.98							0.079	0.144	0.176
18.43	23.50	136.93	0.75	0.93	0.95							0.077	0.140	0.171
19.03	45.07	156.93	0.73	0.90	0.93							0.075	0.136	0.167
19.83	51.27	186.93	0.71	0.88	0.90							0.073	0.133	0.163
20.13	80.69	226.93	0.69	0.86	0.88							0.071	0.129	0.158
20.43	87.33	246.93	0.67	0.83	0.85							0.069	0.126	0.154
20.53	102.55	246.93	0.65	0.81	0.85							0.067	0.122	0.154
20.53	105.67	286.93	0.65	0.79	0.80							0.067	0.118	0.145
21.73	116.22	306.93	0.62	0.76	0.78							0.063	0.115	0.141
21.83	119.53	386.93	0.60	0.74	0.76							0.061	0.111	0.136
22.13	140.43	426.93	0.58	0.71	0.73							0.059	0.108	0.132
22.33	161.52	466.93	0.56	0.69	0.71							0.057	0.104	0.127
23.23	168.47	476.93	0.54	0.67	0.68							0.055	0.101	0.123
24.23	172.88	486.93	0.52	0.64	0.66							0.053	0.097	0.119
24.63	193.02	566.93	0.50	0.62	0.63							0.051	0.093	0.114
25.03	194.29	576.93	0.48	0.60	0.61							0.049	0.090	0.110
25.23	212.90	586.93	0.46	0.57	0.59							0.047	0.086	0.105
26.33	226.13	696.93	0.44	0.55	0.56							0.045	0.083	0.101
26.73	263.43	846.93	0.42	0.52	0.54							0.043	0.079	0.097
27.73	277.10	906.93	0.40	0.50	0.51							0.041	0.075	0.092
27.83	283.57	946.93	0.38	0.48	0.49							0.039	0.072	0.088
27.93	364.31	1006.9	0.37	0.45	0.46							0.037	0.068	0.084
30.43	393.09	1106.9	0.35	0.43	0.44							0.035	0.065	0.079
30.43	396.84	1216.9	0.35	0.40	0.41							0.035	0.061	0.075
31.03	455.25	1256.9	0.31	0.38	0.39							0.032	0.057	0.070
31.73	474.25	1296.9	0.29	0.36	0.37							0.030	0.054	0.066
31.83	474.30	1326.9	0.27	0.33	0.34							0.028	0.050	0.062
32.13	485.15	1366.9	0.25	0.31	0.32							0.026	0.047	0.057
32.33	496.86	1486.9	0.23	0.29	0.29							0.024	0.043	0.053
35.13	508.68	1646.9	0.21	0.26	0.27							0.022	0.039	0.048
35.23	547.62	1806.9	0.19	0.24	0.24							0.020	0.036	0.044
35.63	563.72	1826.9	0.17	0.21	0.22							0.018	0.032	0.040
36.43	617.60	1876.9	0.15	0.19	0.20							0.016	0.029	0.035
38.83	627.52	2006.9	0.13	0.17	0.17							0.014	0.025	0.031
39.23	636.35	2056.9	0.12	0.14	0.15							0.012	0.022	0.026
39.43	650.60	2386.9	0.10	0.12	0.12							0.010	0.018	0.022
42.03	651.19	2466.9	0.08	0.10	0.10							0.008	0.014	0.018
42.13	670.70	2536.9	0.06	0.07	0.07							0.006	0.011	0.013
42.53	671.36	2716.9	0.04	0.05	0.05							0.004	0.007	0.009
44.53	751.44	2736.9	0.02	0.02	0.02							0.002	0.004	0.004
46.93	763.52	3126.9	0.00	0.00	0.00							0	0.000	0.000

36/88 = 0.41

46/88 = 0.52

47/88 = 0.53

13/52 = 0.25

12/42 = 0.29

14/41 = 0.34

Table 3.3.1.3-2: Flow sustainability Indices of the Niger River at Koulikoro, Mali.

<b>Drought Impacts on Discharges</b>	<b>Ranking for Sustainability</b>		
	Annual Minimum Discharges	Annual Mean Discharges	Annual Maximum Discharges
Single Year Deficits	3	2	1
Cumulative Deficits	2	1	3
Duration of Deficits	3	1	2
<b>Overall</b>	<b>3</b>	<b>1</b>	<b>3</b>

Table 3.3.1.3-3: Ranking of flow types by sustainability indices

Figure 3.3.1.3-1 shows the sustainability index as a function of the volume of deficit in each of the three annual flow types. For the annual minimum flows, the graph of the sustainability indices is characterized by a steep slope, meaning a high sensitivity to deficits, that is, they become unsustainable even for small deficits. Next to the annual minimum flows are the annual mean flows with the second steepest slope of the graph of the sustainability indices. The sustainability of the annual maximum flows decreases at a slower rate compared to those of the two other flow types.

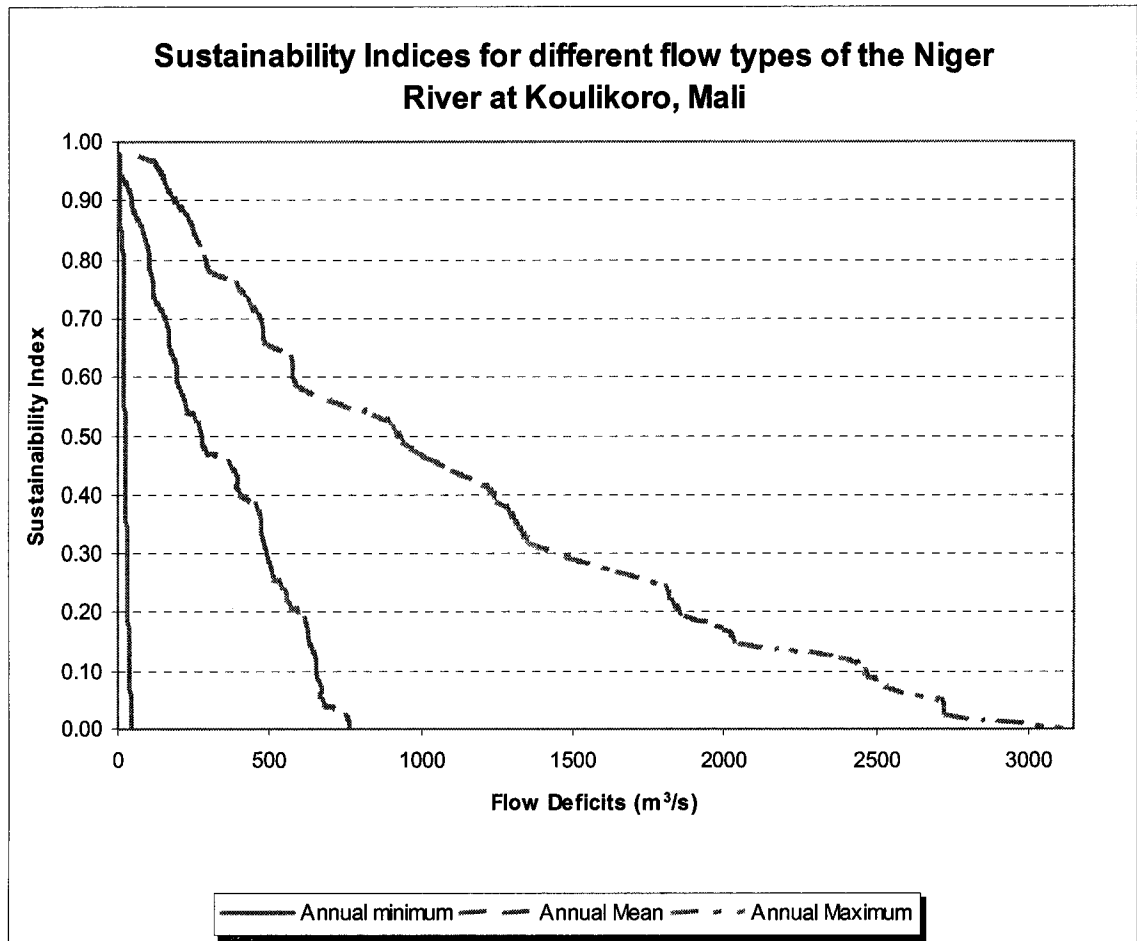


Figure 3.3.1.3-1: Sustainability Indices of different flow types of the Niger River at Koulikoro, Mali

### 3.3.2. Bani River at Douna, Mali

The Bani River is a tributary that discharges annually an average volume of 13.15 km<sup>3</sup> of water into the Niger River. The Douna gaging station is located on the Bani River before it enters into the Inner Delta in where it joins the Niger River proper. At this gaging station, the long-term average discharges of the Bani River are 11.75 m<sup>3</sup>/s for the minimum flows, 416.82 m<sup>3</sup>/s for the annual mean flows, and 1676.70 m<sup>3</sup>/s for the annual maximum flows; they

are used as threshold values. As shown by the graphs of figure 3.3.2-1, there has been a trend of consistent decrease in all the flow types of the Bani River since the early 1970s.

### **3.3.2.1. Characteristics of flow deficits**

Except for the annual mean discharges of 1994, all the annual flows have consistently been below their long-term average values. These sustained deficits for over twenty years seem not to be just caused by only rainfall deficits. Rather, changes in land-use and other factors may be at issue. Whatever the causes, with the maximum annual deficits reaching 100% for the annual minimum flows, 83% for the annual mean and annual maximum flows, they are large enough to suggest a change in the long-term annual average values. By taking this potential change into account, since the early 1970s, the average values would be:

- ✓ 2.52 m<sup>3</sup>/s instead of 11.75 m<sup>3</sup>/s for the annual minimum discharges;
- ✓ 207.53 m<sup>3</sup>/s instead of 416.82 m<sup>3</sup>/s for the annual mean discharges;
- ✓ 921.17 m<sup>3</sup>/s instead of 1676.70 m<sup>3</sup>/s for the annual maximum discharges.

Although this trend is apparent in the analysis, there is no guarantee that the trend will continue in the future. Also the use of the threshold values based upon the entire period of record will yield more conservative (larger deficits) estimates for this analysis.

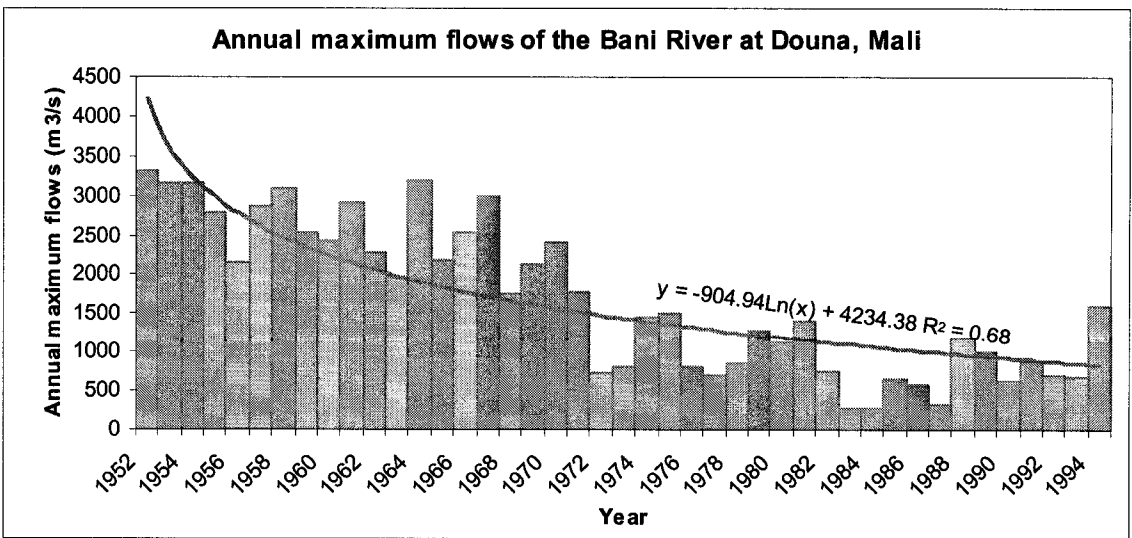
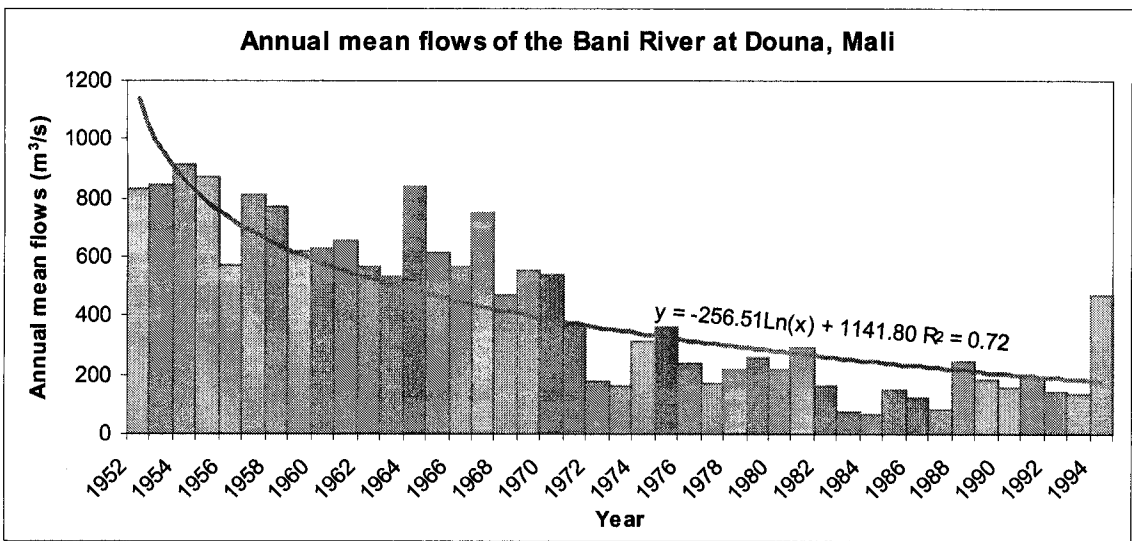
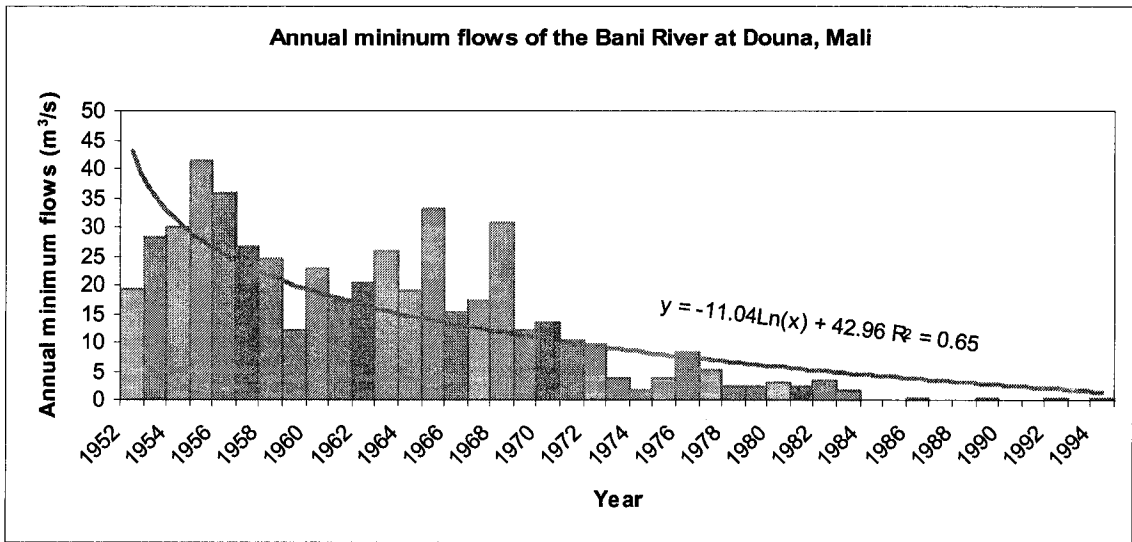


Figure 3.3.2-1: Annual flows of the Bani River at Douna, Mali

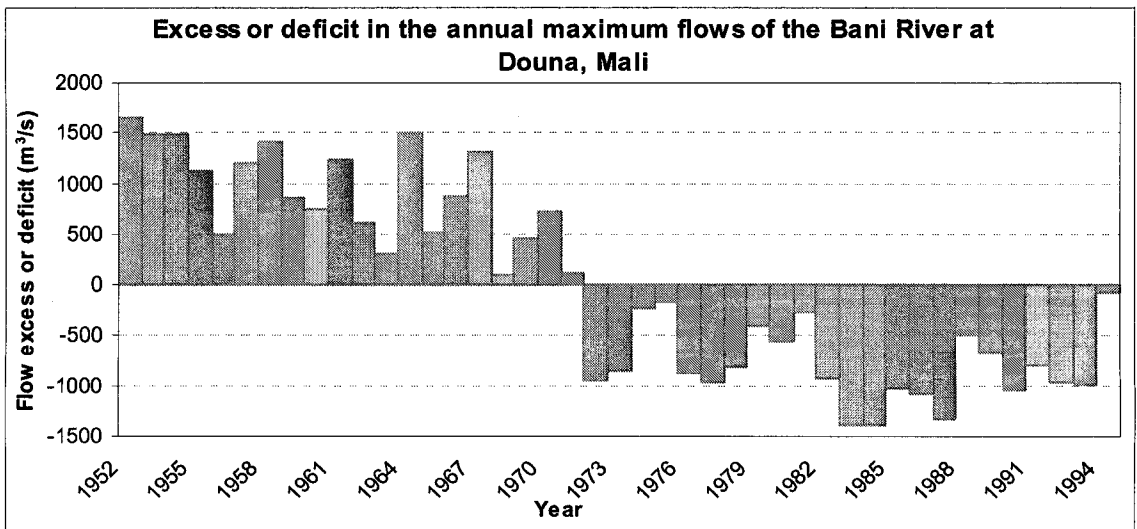
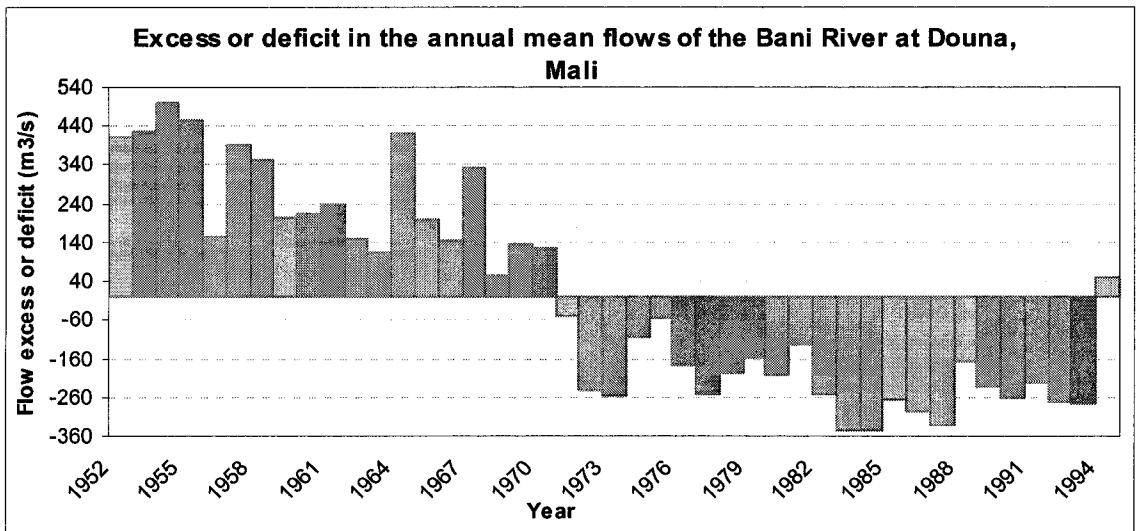
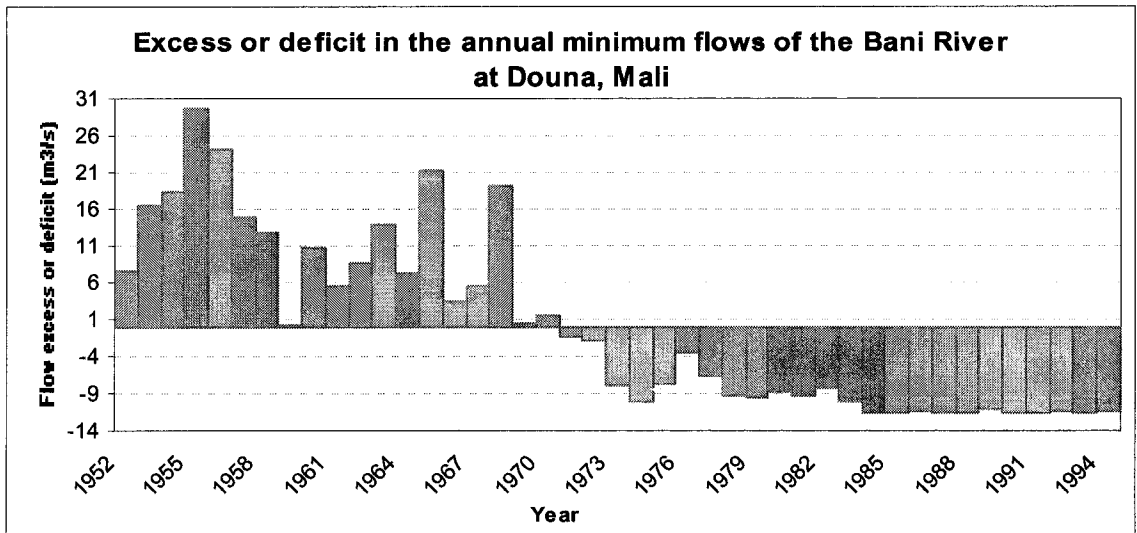


Figure 3.3.2.1-1: Excess or deficits in flows of the Bani River at Douna, Mali

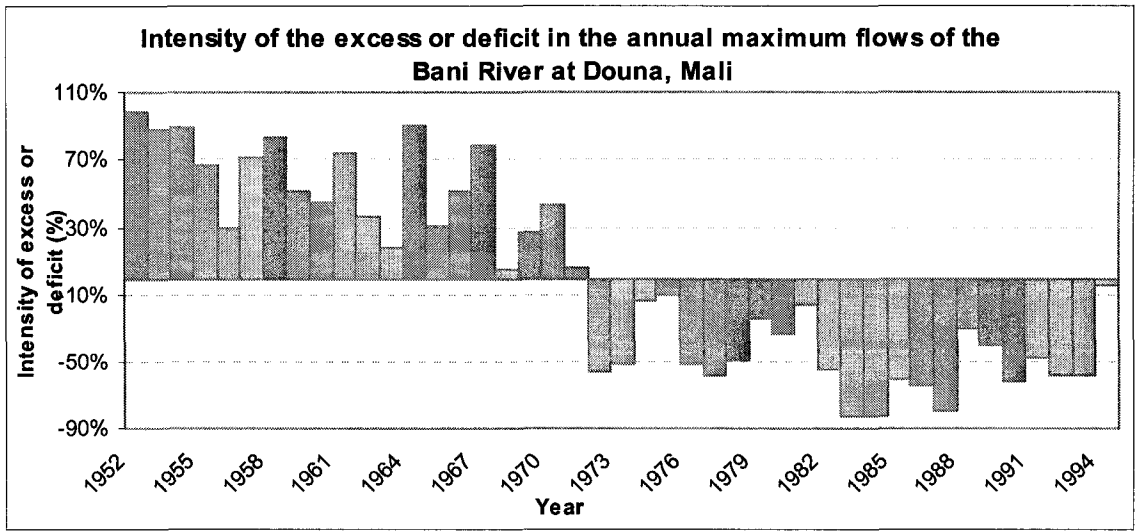
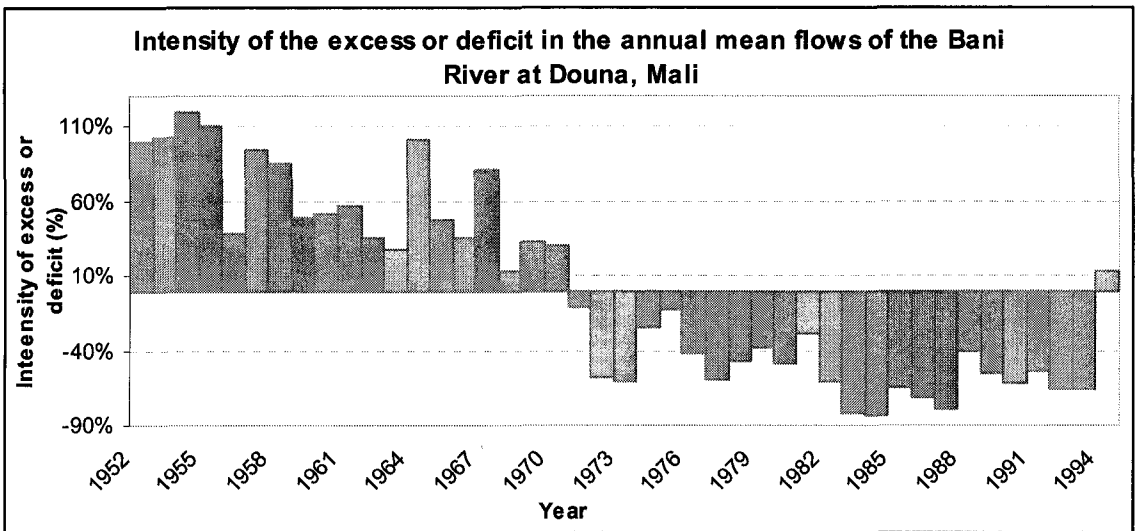
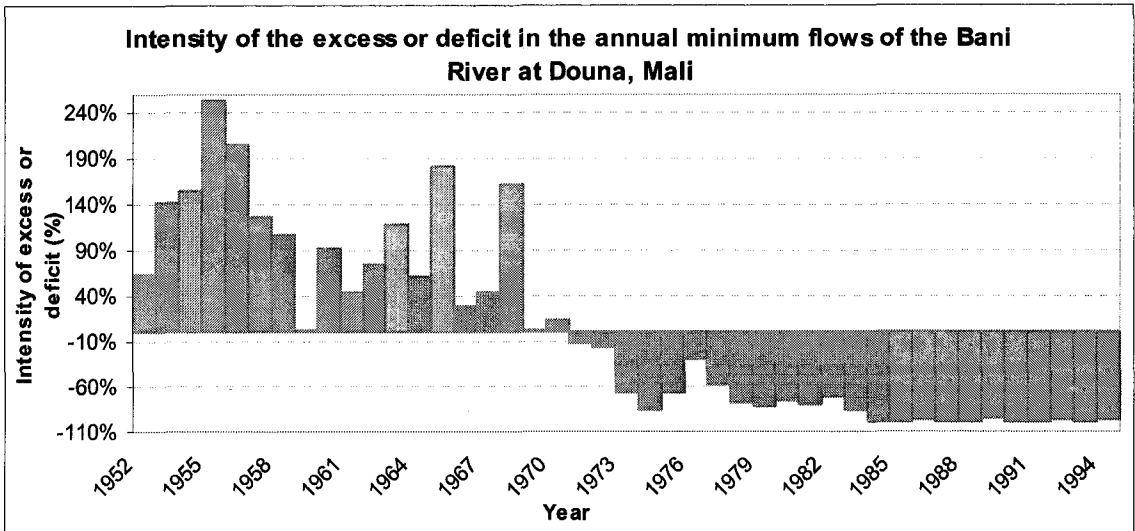


Figure 3.3.2.1-2: Intensity of deficit or excess in the flows of the Bani River at Douna, Mali

Discharge Type	Deficits Sequence	Deficit Timing		Run length (Year)	Intensity (%)	
		Start (Year)	End (Year)		Average	Maximum
Annual Minimum flow	1	1971	1994	24	79	100
Annual Mean flow	1	1971	1993	23	50	83
Annual Maximum flow	1	1972	1994	23	47	83

Table 3.3.2.1-1: Intensity of deficits in the flows of the Bani River at Douna, Mali

### 3.3.2.2. Statistics and distribution of the deficits, cumulative deficits and run lengths

The deficits data of Figure 3.3.2.1-1 were used to generate the histograms of the deficits in the three flow types of the Bani River at Douna; their statistics are given in Table 3.3.2.2-1, below.

Statistics	Deficits in annual		
	Minimum discharge	Mean Discharge	Maximum Discharge
Mean	5.15	118.01	424.33
Standard Error	0.79	19.33	74.20
Median	3.46	54.27	166.70
Standard Deviation	5.18	126.73	486.59
Sample Variance	26.80	16061.26	236766.20
Kurtosis	-1.89	-1.51	-1.22
Skewness	0.14	0.40	0.60
Coefficient of variation	1.01	1.07	1.15
Range	11.75	346.83	1388.70
Minimum	0	0	0
Maximum	11.75	346.83	1388.70

Table 3.3.2.2-1: Statistics of the deficits in the Flows of the Bani River at Douna, Mali

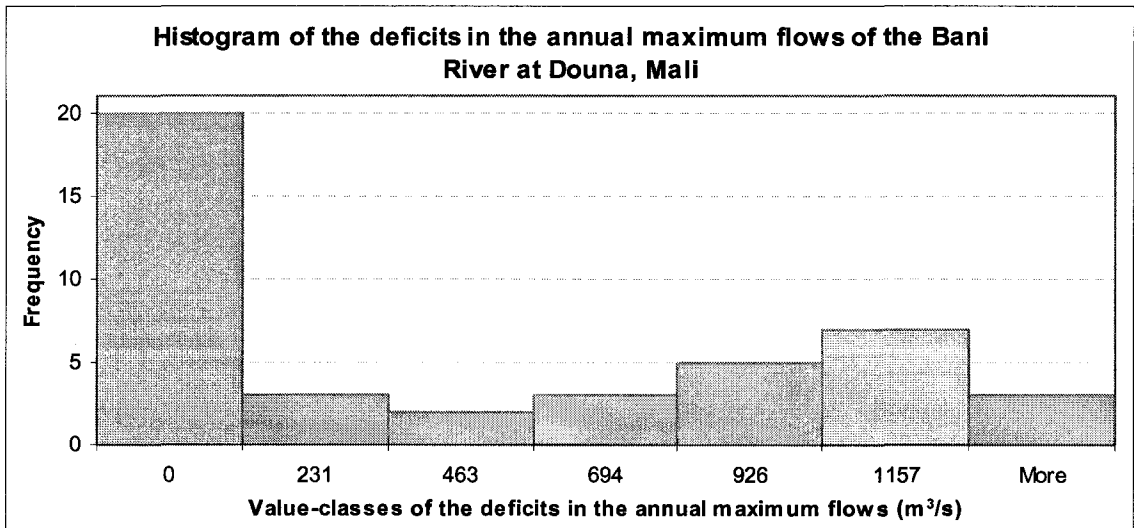
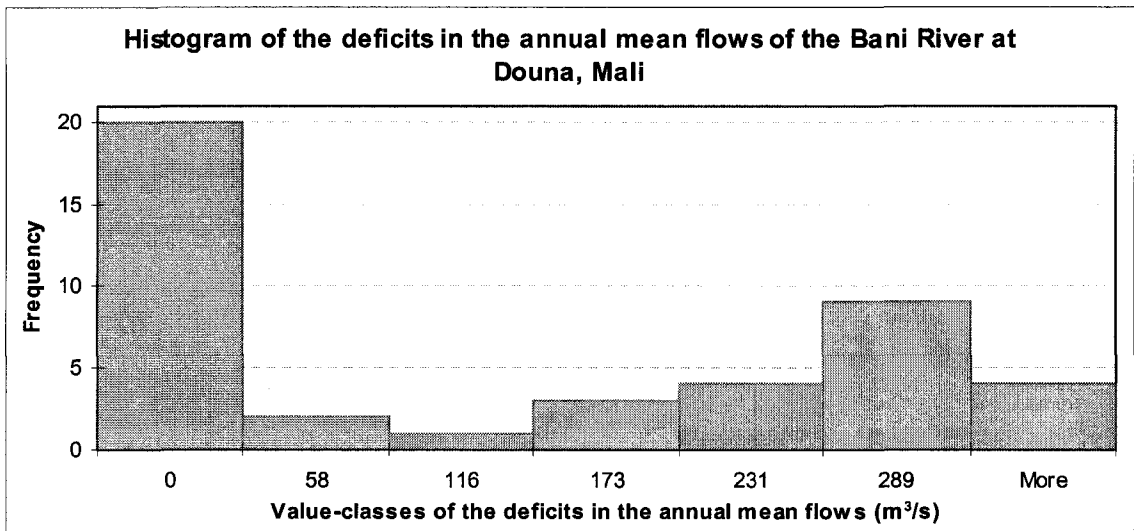
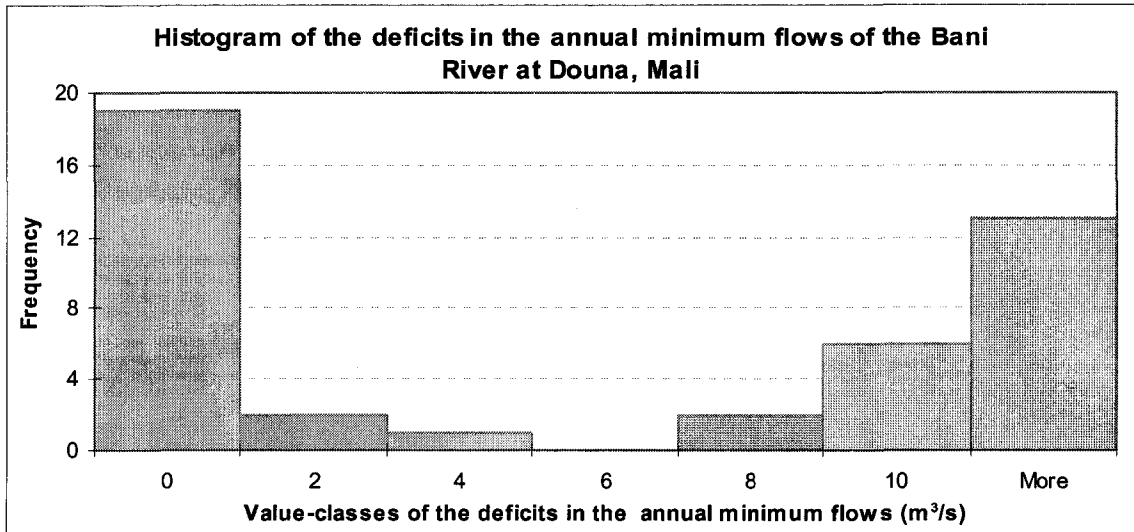


Figure 3.3.2.2-1: Histograms of the deficits in the flows of the Bani River at Douna, Mali

The beta probability distribution function was fitted to the data of deficits in all the three flow types; the initial moment estimators of the parameters were optimized by the least squares method.

Fitted probability function		Deficits in annual		
		Minimum discharge	Mean Discharge	Maximum Discharge
Type		Beta	Beta	Beta
Parameters Estimators	$\hat{\alpha} =$	0.14	0.32	0.22
	$\hat{\beta} =$	0.23	0.57	0.48
Coefficient of determination		0.99	0.99	0.98

Table 3.3.2.2-2: Probability distribution functions fitted to the deficits in the flows of the Bani River at Douna, Mali

Order	Volume of deficits in Annual Discharge (m <sup>3</sup> /s)			Return Period of deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of deficits in			CDF of Fitted Distribution to deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Beta	Annual Mean flows: Beta	Annual Maximum flows: Beta
1	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
2	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
3	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
4	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
5	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
6	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
7	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
8	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
9	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
10	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
11	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
12	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
13	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
14	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
15	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
16	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
17	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
18	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
19	0	0	0	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
20	1.35	0	0	1.83	1.02	1.02	0.45	0.45	0.02	0.40	0.00	0.00
21	1.95	47.25	66.70	1.91	1.91	1.91	0.48	0.48	0.48	0.43	0.41	0.39
22	3.46	54.27	166.70	2.00	2.00	2.00	0.50	0.50	0.50	0.49	0.43	0.49
23	6.74	101.94	226.70	2.10	2.10	2.10	0.52	0.52	0.52	0.58	0.53	0.52
24	7.80	120.64	256.70	2.20	2.20	2.20	0.55	0.55	0.55	0.61	0.57	0.54
25	7.87	157.56	396.70	2.32	2.32	2.32	0.57	0.57	0.57	0.61	0.63	0.60
26	8.23	168.96	486.70	2.44	2.44	2.44	0.59	0.59	0.59	0.62	0.65	0.63
27	8.71	175.51	556.70	2.59	2.59	2.59	0.61	0.61	0.61	0.64	0.66	0.66
28	9.21	199.28	666.70	2.75	2.75	2.75	0.64	0.64	0.64	0.66	0.69	0.69
29	9.31	201.39	801.70	2.93	2.93	2.93	0.66	0.66	0.66	0.66	0.70	0.73
30	9.48	222.57	818.70	3.14	3.14	3.14	0.68	0.68	0.68	0.67	0.73	0.74
31	10.06	231.35	861.70	3.38	3.38	3.38	0.70	0.70	0.70	0.69	0.74	0.75
32	10.13	240.46	870.70	3.67	3.67	3.67	0.73	0.73	0.73	0.69	0.75	0.75
33	11.24	248.81	923.70	4.00	4.00	4.00	0.75	0.75	0.75	0.77	0.77	0.77
34	11.28	252.16	947.70	4.40	4.40	4.40	0.77	0.77	0.77	0.77	0.77	0.77
35	11.36	255.02	975.70	4.89	4.89	4.89	0.80	0.80	0.80	0.78	0.78	0.78
36	11.48	259.39	975.70	5.50	5.50	4.89	0.82	0.82	0.80	0.80	0.78	0.78
37	11.62	268.40	988.70	6.29	6.29	6.29	0.84	0.84	0.84	0.83	0.80	0.79
38	11.64	272.51	1019.70	7.33	7.33	7.33	0.86	0.86	0.86	0.84	0.80	0.80
39	11.69	277.73	1036.70	8.80	8.80	8.80	0.89	0.89	0.89	0.86	0.81	0.80
40	11.73	296.47	1086.70	11.00	11.00	11.00	0.91	0.91	0.91	0.89	0.84	0.82
41	11.75	332.15	1337.70	14.67	14.67	14.67	0.93	0.93	0.93	0.93	0.92	0.92
42	11.75	343.81	1388.70	14.67	22.00	22.00	0.93	0.93	0.95	0.93	0.96	0.97
43	11.75	346.83	1388.70	14.67	44.00	22.00	0.93	0.93	0.95	0.93	0.97	0.97
Coefficient of determination R <sup>2</sup> =										0.99	0.99	0.98

Table 3.3.2.2-3: CDFs of empirical and fitted probability distributions of the deficits in the flows of Bani River at Douna, Mali

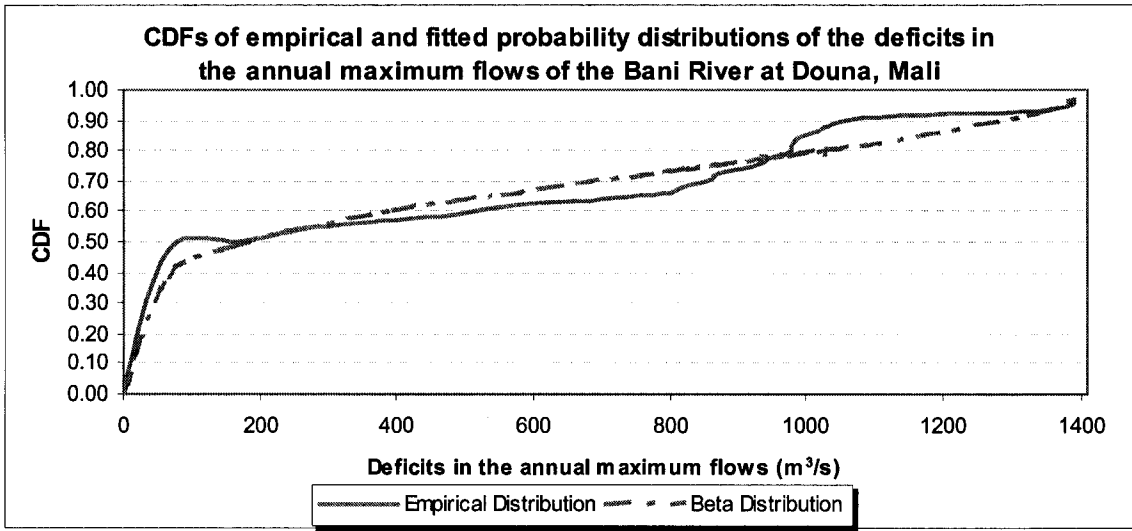
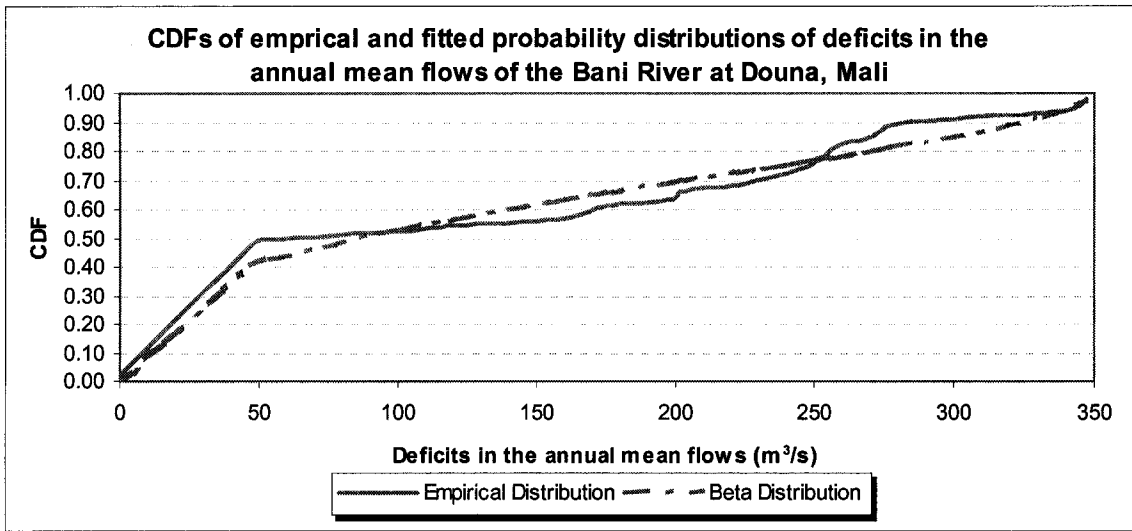
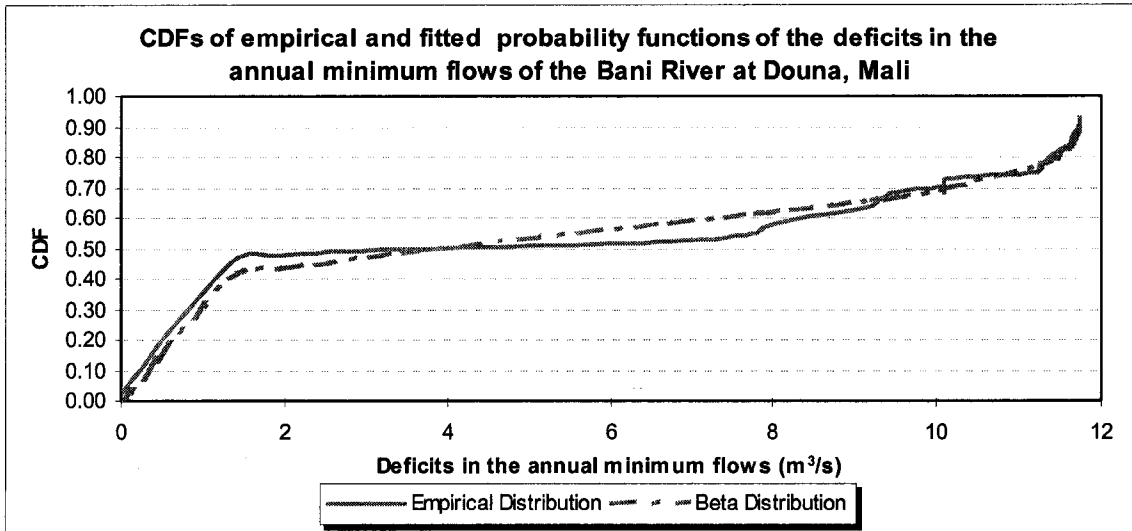


Figure 3.3.2.2-2: CDFs of probability distributions of the deficits in the flows of the Bani River at Douna, Mali

With only two elements in the time-series of the cumulative deficits and their duration, they were excluded from further analysis.

### **3.3.2.3. Sustainability of flows**

The results of the sustainability assessment of the different flows of the Bani River are shown in the following tables 3.3.2.3-1, 3.3.2.3-2, 3.3.2.3-3 and graph in Figure 3.3.2.3-1.

From the graph, it can be noticed that the annual minimum and maximum flows are unsustainable at any deficit levels. The annual mean discharges have a slim margin of sustainability, which, too, decreases at a steep rate.

<b>Drought Impacts on Discharges</b>	<b>Performance Indicator</b>	<b>Annual Minimum Discharges</b>	<b>Annual Mean Discharges</b>	<b>Annual Maximum Discharges</b>
<b>Single Year Deficits</b>	Reliability	19/43 = 0.44	20/43 = 0.47	20/43 = 0.47
	Resilience	0/43 = 0	1/43 = 0.02	0/43 = 0
	Expected Deficit (m <sup>3</sup> /s)	221.51/24 = 9.23	5074.47/23 = 220.63	18246.05/23 = 793.31
	Expected Vulnerability	0.63	0.61	0.65
	Sustainability	0	0.007	0
<b>Cumulative Deficits</b>	Reliability	1/2 = 0.5	2/3 = 0.67	1/2 = 0.5
	Resilience	0	1/1 = 1	0
	Expected Deficit (m <sup>3</sup> /s)	221.51	5074.47	18246.05
	Expected Vulnerability	0	0	0
	Sustainability	0	0	0
<b>Deficits Duration</b>	Reliability	1/2 = 0.5	2/3 = 0.67	1/2 = 0.5
	Resilience	0/1 = 0	1/1 = 1	0/1 = 0
	Expected Duration	24	23	23
	Expected Vulnerability	0	0	0
	Sustainability	0.00	0.00	0.00
<b>Relative Sustainability</b>		<b>0.000</b>	<b>0.007</b>	<b>0.000</b>

Table 3.3.2.3-1: Flow Sustainability Indices for the expected values of flow deficits and duration of deficit in the flows of the Bani River at Douna, Mali

<b>Drought Impacts on Discharges</b>	<b>Ranking for Sustainability</b>		
	<b>Annual Minimum Discharges</b>	<b>Annual Mean Discharges</b>	<b>Annual Maximum Discharges</b>
Single Year Deficits	2	1	2
Cumulative Deficits	1	1	1
Deficits Duration	1	1	1
<b>Overall</b>	<b>2</b>	<b>1</b>	<b>1</b>

Table 3.3.2.3-2: Ranking of the flows by sustainability Indices of the Bani River at Douna, Mali

Deficit in Annual Discharge (m <sup>3</sup> /s)			Vulnerability (Exceedence Probability)			Reliability			Resilience			Sustainability Index		
Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
1.35			0.96			19/43 = 0.44			0/43 = 0	1/43 = 0.02	0/43 = 0	0		
1.95	47.25	66.70	0.92	0.96	0.96							0	0.010	0.000
3.46	54.27	166.70	0.88	0.91	0.91							0	0.010	0.000
6.74	101.94	226.70	0.83	0.87	0.87							0	0.009	0.000
7.80	120.64	256.70	0.79	0.83	0.83							0	0.009	0.000
7.87	157.56	396.70	0.75	0.78	0.78							0	0.008	0.000
8.23	168.96	486.70	0.71	0.74	0.74							0	0.008	0.000
8.71	175.51	556.70	0.67	0.70	0.70							0	0.008	0.000
9.21	199.28	666.70	0.63	0.65	0.65							0	0.007	0.000
9.31	201.39	801.70	0.58	0.61	0.61							0	0.007	0.000
9.48	222.57	818.70	0.54	0.57	0.57							0	0.006	0.000
10.06	231.35	861.70	0.50	0.52	0.52							0	0.006	0.000
10.13	240.46	870.70	0.46	0.48	0.48							0	0.005	0.000
11.24	248.81	923.70	0.42	0.43	0.43							0	0.005	0.000
11.28	252.16	947.70	0.38	0.39	0.39							0	0.004	0.000
11.36	255.02	975.70	0.33	0.35	0.35							0	0.004	0.000
11.48	259.39	975.70	0.29	0.30	0.35							0	0.003	0.000
11.62	268.40	988.70	0.25	0.26	0.26							0	0.003	0.000
11.64	272.51	1019.7	0.21	0.22	0.22							0	0.002	0.000
11.69	277.73	1036.7	0.17	0.17	0.17							0	0.002	0.000
11.73	296.47	1086.7	0.13	0.13	0.13	0	0.001	0.000						
11.75	332.15	1337.7	0.08	0.09	0.09	0	0.001	0.000						
11.75	343.81	1388.7	0.08	0.04	0.04	0	0.000	0.000						
11.75	346.83	1388.7	0.08	0.00	0.04	0	0.000	0.000						

Table 3.3.2.3-3: Sustainability indices of the flows of the Bani River at Douna, Mali

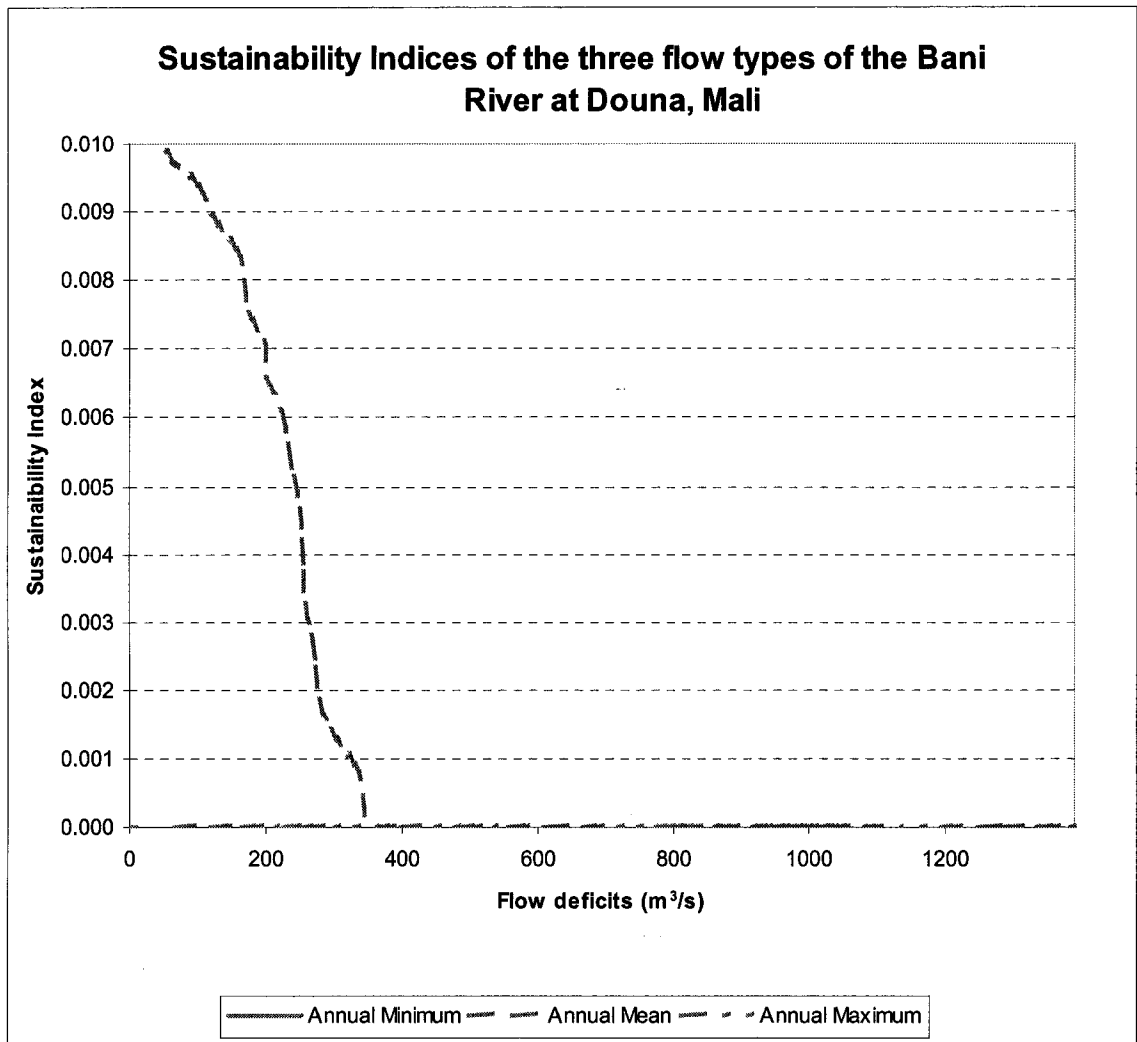


Figure 3.3.2.3-1: Sustainability Indices of different flow types of the Bani River at Douna, Mali

### 3.3.3. The Niger River at Mopti, Mali

The city of Mopti is located in the inner delta where the Niger River receives water from its tributary of the Bani River, and flows through a series of braided and interconnected channels. The flow data analyzed here were collected at the gaging station located at Mopti on one the Niger River proper; the data record is 51 years long. At this gaging station, the threshold

values are 51.38 m<sup>3</sup>/s for the minimum flows, 1003.01 m<sup>3</sup>/s for the annual mean flows, and 2768.82 m<sup>3</sup>/s for the annual maximum flows.

### 3.3.3.1. Characteristics of flow deficits

Figure 3.3.3.1-1 and Figure 3.3.3.1-2 show the deficits in the different flows in terms of volume and intensity for the Niger River at Mopti.

Discharge Type	Deficits sequence	Start (Year)	End (Year)	Run length (Year)	Intensity (%)	
					Average	Maximum
Annual minimum flow	1	1944	1945	2	47	60
	2	1947	1950	4	38	50
	3	1961	1962	2	21	28
	4	1966	1966	1	47	47
	5	1969	1969	1	45	45
	6	1971	1981	11	64	95
	7	1983	1986	4	22	47
	8	1988	1991	4	14	39
	<b>Maximum</b>				<b>11</b>	<b>64%</b>
Average annual mean flow	1	1944	1944	1	18	18
	2	1947	1947	1	3	3
	3	1949	1949	1	8	8
	4	1971	1974	4	22	39
	5	1976	1993	18	36	59
	<b>Maximum</b>				<b>18</b>	<b>36%</b>
Annual maximum flow	1	1944	1944	1	5	5
	2	1972	1973	2	24	27
	3	1976	1978	3	10	22
	4	1980	1993	14	32	53
	<b>Maximum</b>				<b>14</b>	<b>32%</b>

Table 3.3.3.1-1: Intensity of deficits in the flows of the Niger River at Mopti

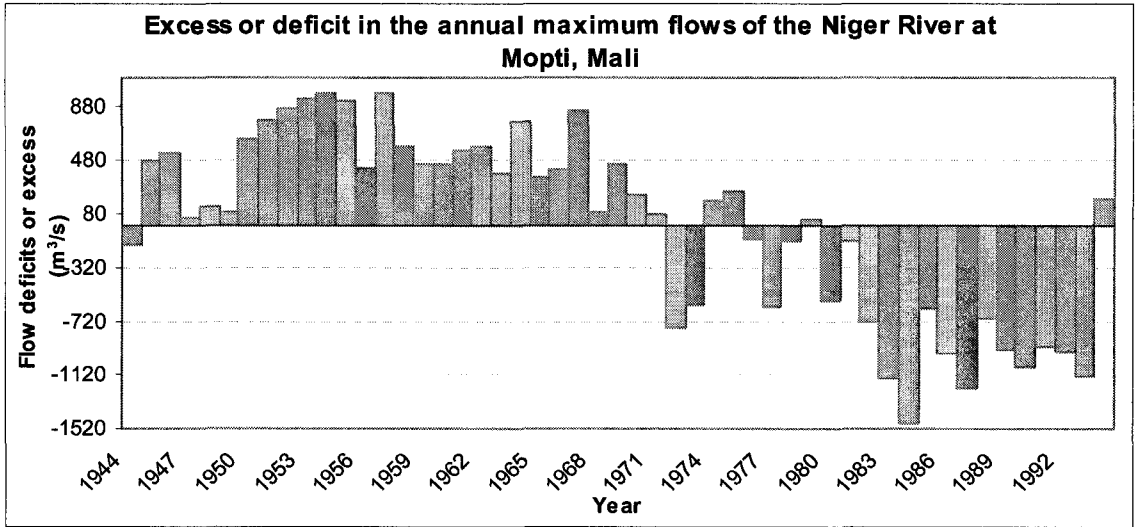
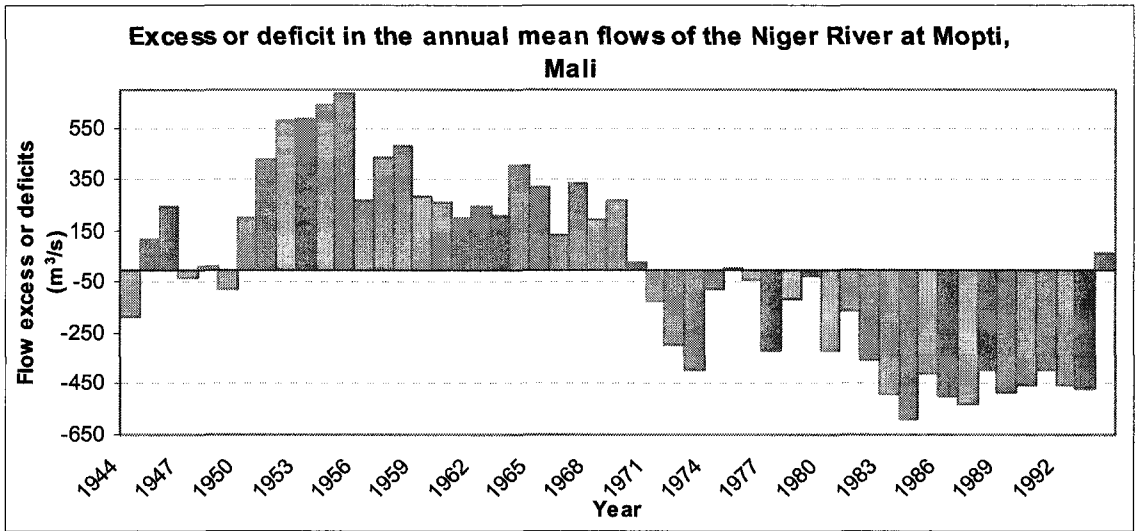
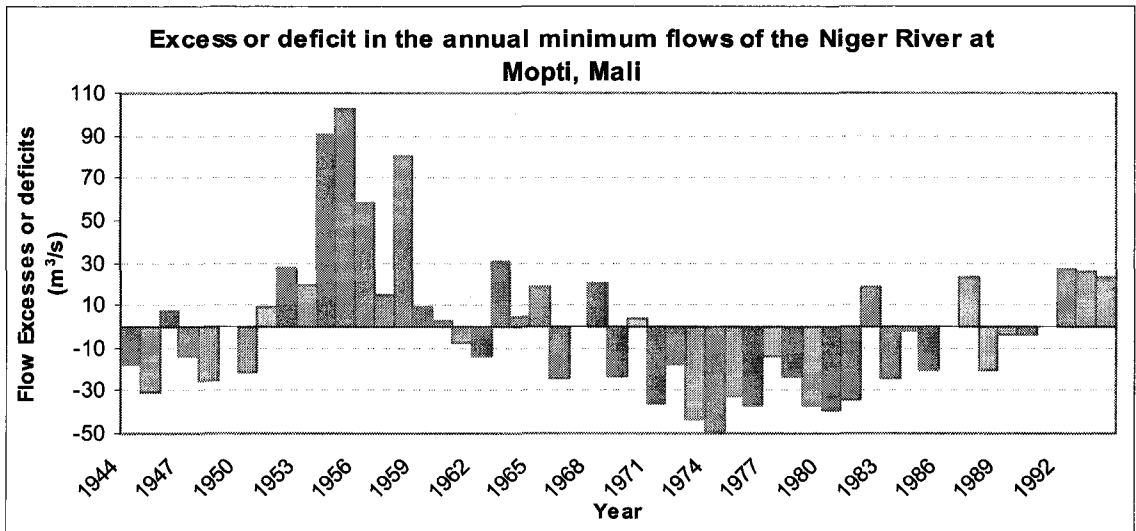


Figure 3.3.3.1-1: Excess or deficits in the annual flow of the Niger River at Mopti, Mali

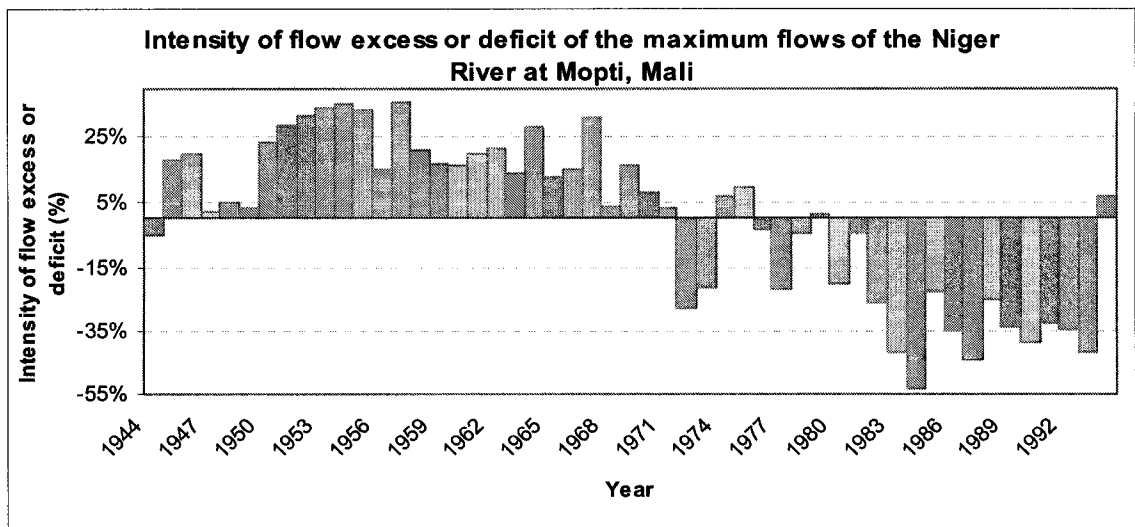
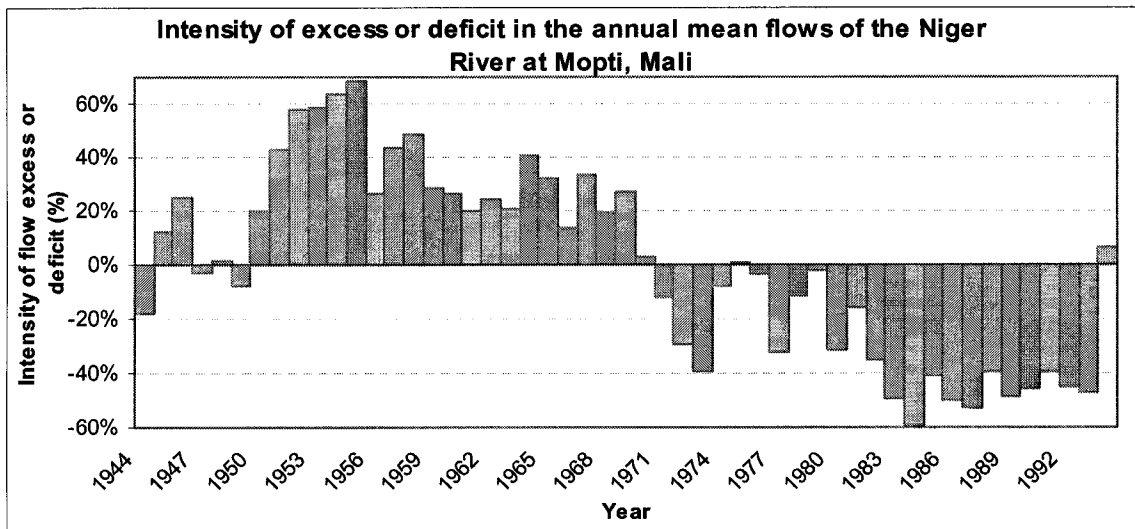
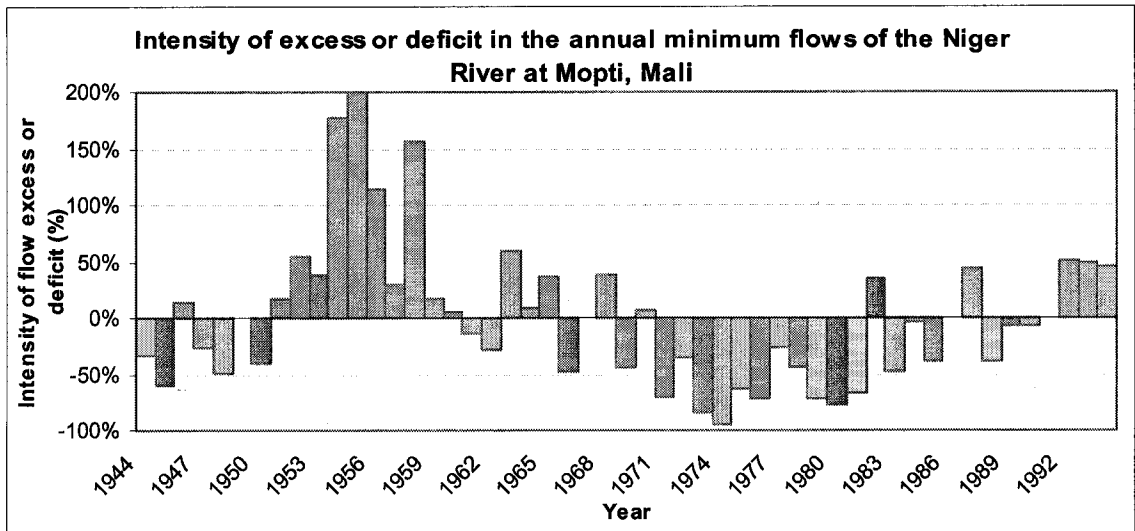


Figure 3.3.3.1-2: Intensity of excess or deficit in the flows of the Niger River at Mopti, Mali

### 3.3.3.2. Statistics and distribution of the deficits, cumulative deficits and run lengths

The statistics of the deficits in the flows are given in Table 3.3.1.2-1.

Statistics	Deficits in annual flows		
	Minimum discharge	Mean Discharge	Maximum Discharge
Mean	12.06	150.43	290.52
Standard Error	2.09	27.88	61.59
Median	1.98	0	0
Standard Deviation	14.89	199.08	439.84
Sample Variance	221.80	39633.84	193456.87
Kurtosis	-0.55	-0.89	-0.04
Skewness	0.87	0.89	1.19
Coefficient of variation	1.23	1.32	1.51
Range	48.96	593.15	1478.82
Minimum	0	0	0
Maximum	48.96	593.15	1478.82
	Cumulative deficits		
Mean	36.27	767.21	1852.06
Standard Error	20.19	642.55	1531.90
Median	10.83	15.75	69.41
Standard Deviation	80.77	2031.93	4332.86
Sample Variance	6523.74	4128730.64	18773678.7
Kurtosis	13.61	9.50	7.68
Skewness	3.59	3.06	2.76
Coefficient of variation	2.23	2.65	2.34
Range	329.41	6498.06	12503.53
Minimum	0	0	0
Maximum	329.41	6498.06	12503.53
	Run length of deficits		
Mean	1.88	2.5	2.38
Standard Error	0.72	1.77	1.70
Median	0.5	0.5	0.5
Standard Deviation	2.90	5.58	4.81
Sample Variance	8.38	31.17	23.13
Kurtosis	6.35	8.68	6.90
Skewness	2.31	2.90	2.59
Coefficient of variation	1.54	2.23	2.02
Range	11	18	14
Minimum	0	0	0
Maximum	11	18	14

Table 3.3.3.2-1: Statistics of the deficits in the annual flows of the Niger River at Mopti, Mali

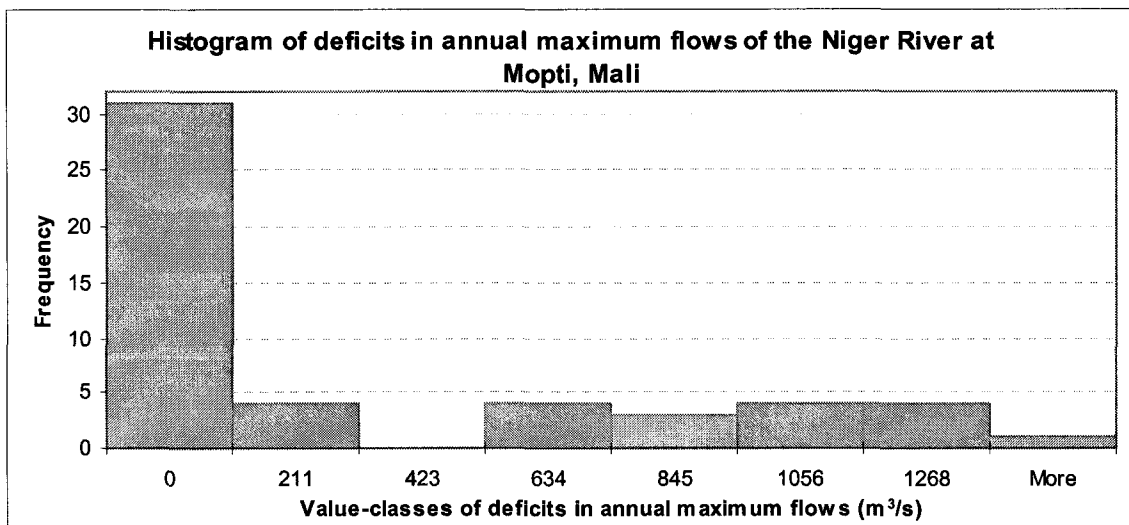
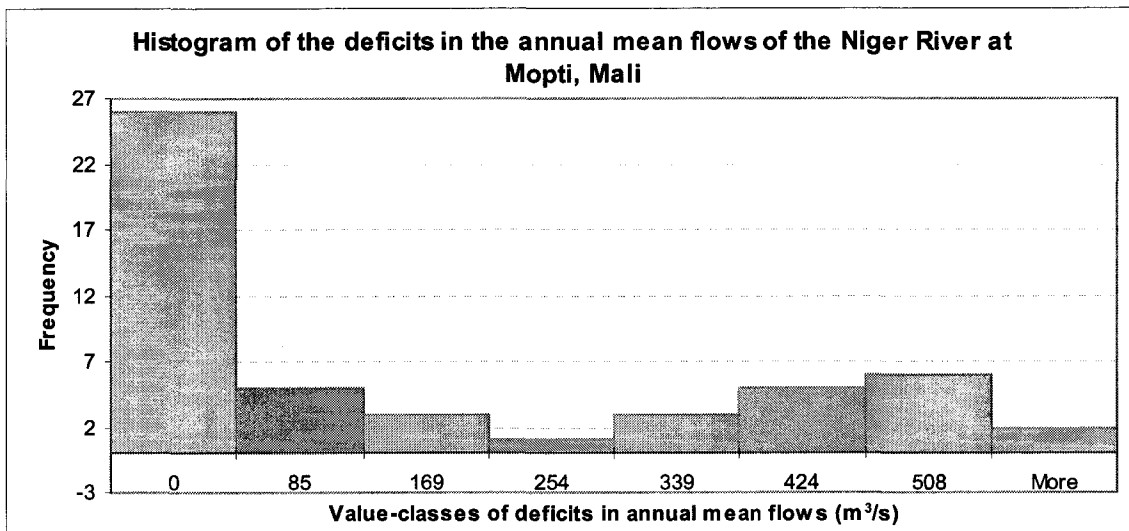
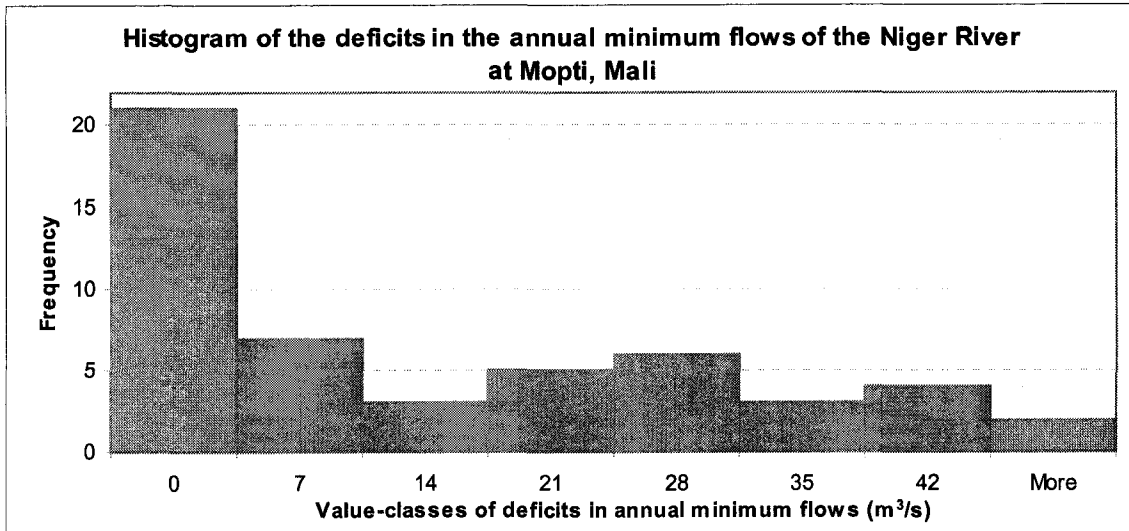


Figure 3.3.3.2-1: Histogram of flow deficits of the Niger River at Mopti, Mali

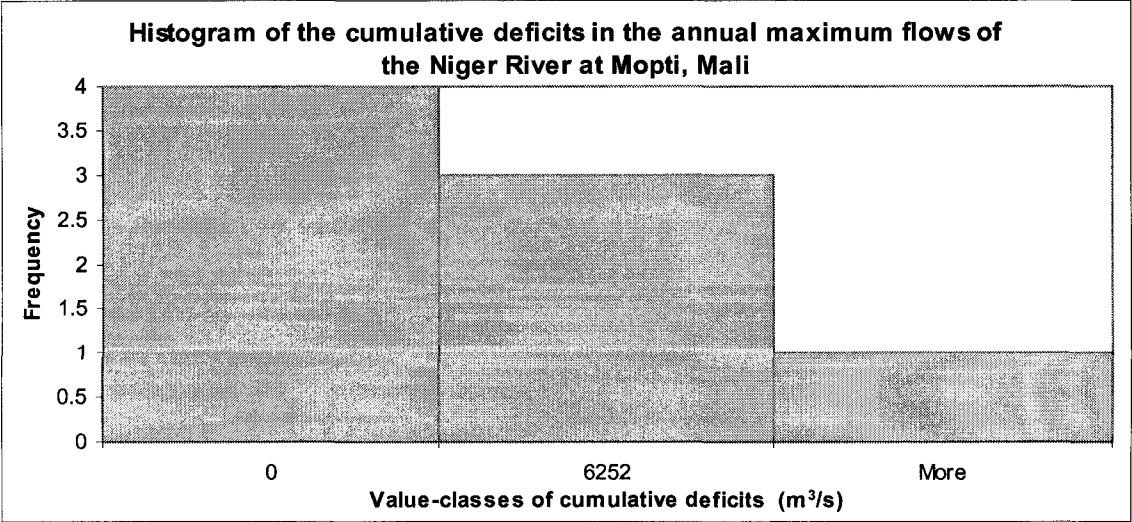
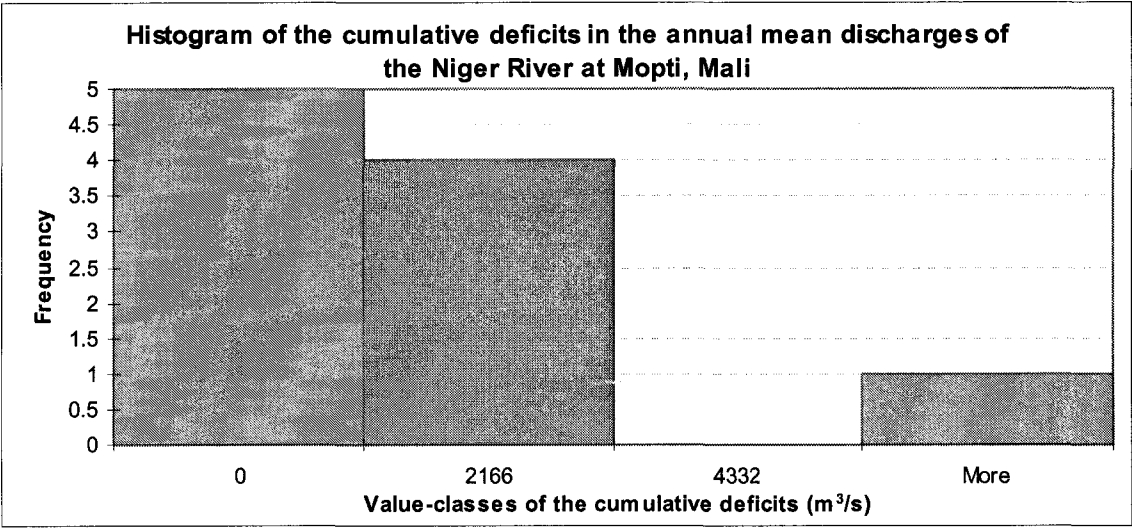
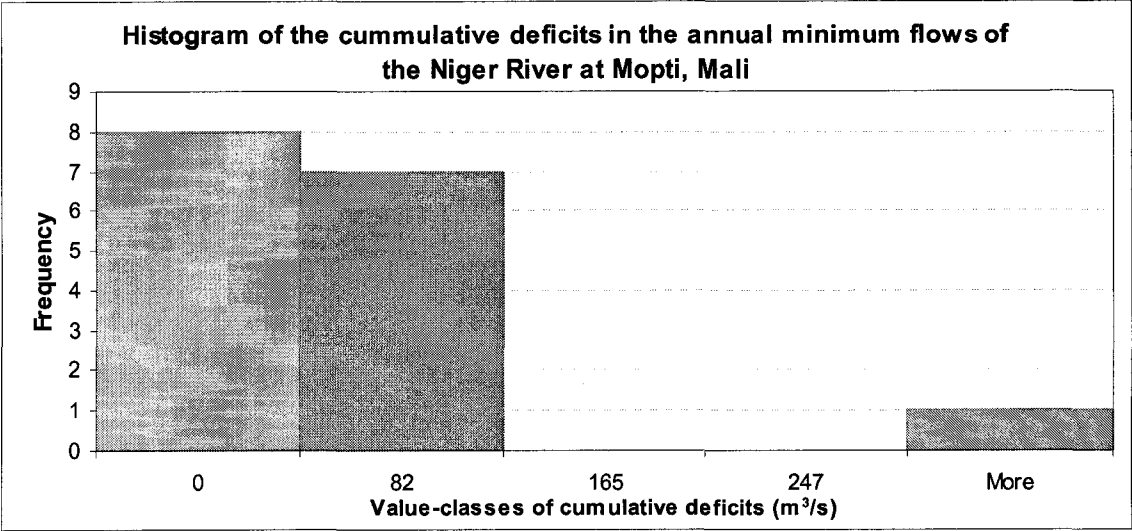


Figure 3.3.3.2-2: Histogram of cumulative deficits in the flow of the Niger River at Mopti, Mali

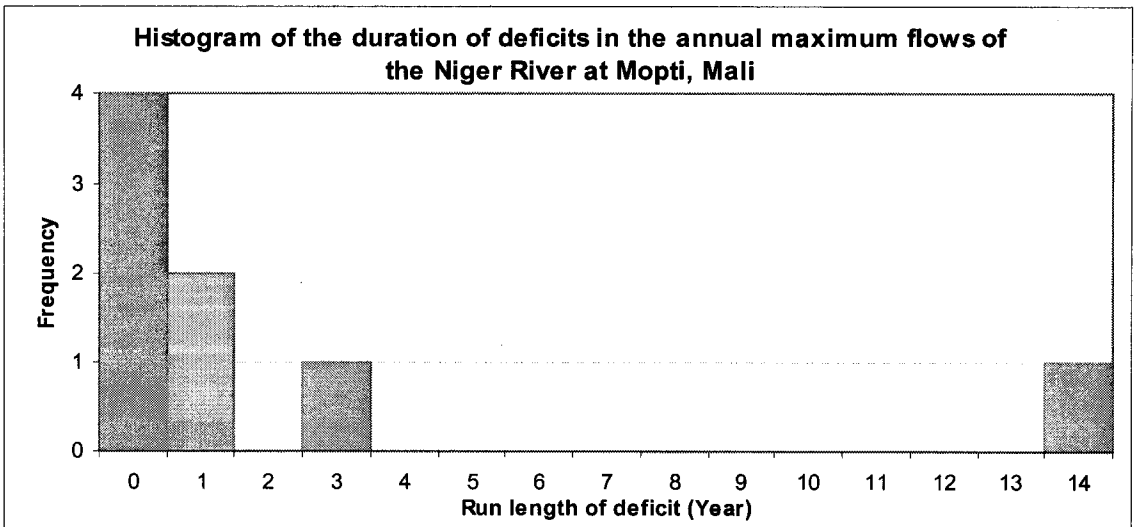
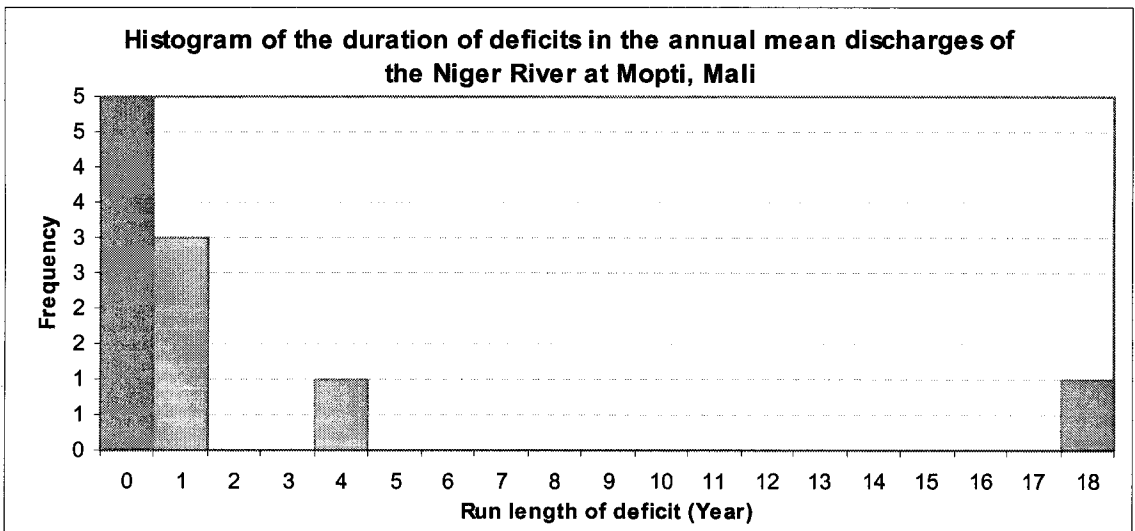
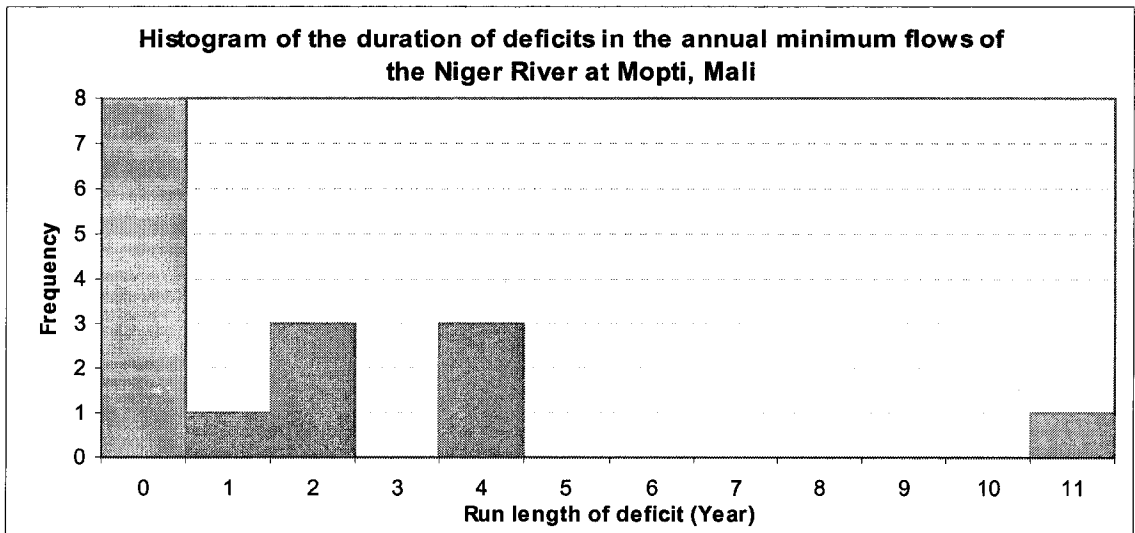


Figure 3.3.3.2-3: Histogram of the durations of deficits in flows of the Niger River at Mopti, Mali

The beta probability distribution function was fitted to data of annual deficits data; the initial values of the moment estimators of the parameters were optimized by least square method. The gamma probability distribution function was fitted to the cumulative deficits and run length of deficits. The results are shown in the tables and figures below.

Fitted probability function		Deficits in annual flows		
		Minimum discharge	Mean Discharge	Maximum Discharge
Type		Beta	Beta	Beta
Parameters Estimators	$\hat{\alpha} =$	0.16	0.57	0.13
	$\hat{\beta} =$	0.54	263.47	0.529
Coefficient of determination		0.97	0.82	0.99
		Cumulative deficits		
Type		Gamma	Gamma	Gamma
Parameters Estimators	$\hat{\alpha} =$	0.20	0.14	0.18
	$\hat{\beta} =$	179.87	5381.52	10136.65
Coefficient of determination		0.96	0.95	0.92
		Run length of deficits		
Type		Gamma	Gamma	Gamma
Parameters Estimators	$\hat{\alpha} =$	0.42	0.20	0.24
	$\hat{\beta} =$	4.47	12.47	9.74
Coefficient of determination		0.94	0.92	0.92

Table 3.3.3.2-2: Parameters of probability distribution functions fitted to the deficits in annual flows of the Niger River at Mopti, Mali

Order	Volume of deficits in Annual Discharge (m <sup>3</sup> /s)			Return Period of deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of deficits in			CDF of Fitted Distribution to deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Beta	Annual Mean flows: Beta	Annual Maximum flows: Beta
1	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
2	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
3	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
4	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
5	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
6	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
7	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
8	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
9	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
10	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
11	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
12	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
13	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
14	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
15	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
16	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
17	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
18	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
19	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
20	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
21	0.00	0.00	0.00	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
22	0.08	0.00	0.00	1.73	1.02	1.02	0.42	0.02	0.02	0.30	0.00	0.00
23	0.18	0.00	0.00	1.79	1.02	1.02	0.44	0.02	0.02	0.34	0.00	0.00
24	0.28	0.00	0.00	1.86	1.02	1.02	0.46	0.02	0.02	0.36	0.00	0.00
25	0.38	0.00	0.00	1.93	1.02	1.02	0.48	0.02	0.02	0.38	0.00	0.00
26	1.98	0.00	0.00	2.00	1.02	1.02	0.50	0.02	0.02	0.50	0.00	0.00
27	3.38	21.44	0.00	2.08	2.08	1.02	0.52	0.52	0.02	0.55	0.51	0.00
28	3.78	31.51	0.00	2.17	2.17	1.02	0.54	0.54	0.02	0.56	0.54	0.00
29	7.28	39.05	0.00	2.26	2.26	1.02	0.56	0.56	0.02	0.62	0.56	0.00
30	13.48	77.83	0.00	2.36	2.36	1.02	0.58	0.58	0.02	0.70	0.62	0.00
31	13.58	78.36	0.00	2.48	2.48	1.02	0.60	0.60	0.02	0.70	0.62	0.00
32	14.38	114.29	98.82	2.60	2.60	2.60	0.62	0.62	0.62	0.71	0.66	0.61
33	17.28	122.71	118.82	2.74	2.74	2.74	0.63	0.63	0.63	0.73	0.67	0.63
34	17.98	160.89	118.82	2.89	2.89	2.74	0.65	0.65	0.63	0.74	0.70	0.63
35	19.98	180.95	138.82	3.06	3.06	3.06	0.67	0.67	0.67	0.75	0.71	0.64
36	20.28	291.94	558.82	3.25	3.25	3.25	0.69	0.69	0.69	0.76	0.78	0.78
37	21.08	316.05	588.82	3.47	3.47	3.47	0.71	0.71	0.71	0.76	0.79	0.79
38	22.98	320.25	608.82	3.71	3.71	3.71	0.73	0.73	0.73	0.78	0.80	0.79
39	22.98	352.58	618.82	3.71	4.00	4.00	0.73	0.75	0.75	0.78	0.81	0.80
40	23.98	390.70	688.82	4.33	4.33	4.33	0.77	0.77	0.77	0.78	0.83	0.81
41	24.28	392.28	718.82	4.73	4.73	4.73	0.79	0.79	0.79	0.78	0.83	0.82
42	25.48	397.22	758.82	5.20	5.20	5.20	0.81	0.81	0.81	0.79	0.83	0.82
43	30.58	405.21	898.82	5.78	5.78	5.78	0.83	0.83	0.83	0.83	0.84	0.85
44	32.58	453.80	938.82	6.50	6.50	6.50	0.85	0.85	0.85	0.84	0.86	0.86

Table 3.3.3-3: Probability distributions of deficits in the flows of the Niger River at Mopti, Mali

Order	Volume of deficits in Annual Discharge (m <sup>3</sup> /s)			Return Period of deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of deficits in			CDF of Fitted Distribution to deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Beta	Annual Mean flows: Beta	Annual Maximum flows: Beta
45	34.68	455.73	948.82	7.43	7.43	7.43	0.87	0.87	0.87	0.85	0.87	0.86
46	36.28	470.31	958.82	8.67	8.67	8.67	0.88	0.88	0.88	0.87	0.87	0.86
47	36.98	486.41	1068.82	10.40	10.40	10.40	0.90	0.90	0.90	0.87	0.88	0.88
48	37.08	493.91	1138.82	13.00	13.00	13.00	0.92	0.92	0.92	0.87	0.89	0.89
49	39.28	498.66	1148.82	17.33	17.33	17.33	0.94	0.94	0.94	0.89	0.89	0.90
50	43.69	526.84	1218.82	26.00	26.00	26.00	0.96	0.96	0.96	0.92	0.91	0.91
51	48.96	593.15	1478.82	52.00	52.00	52.00	0.98	0.98	0.98	0.97	0.99	1.00
Coefficient of determination R <sup>2</sup> =										0.97	0.82	0.99

Table 3.3.2-3 (Continued): CDFs of empirical and fitted probability distributions of flow deficits of the Niger River at Mopti, Mali

Order	Volume of cumulative deficits in Discharge (m <sup>3</sup> /s)			Return Period of cumulative deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of cumulative deficits in			CDF of Fitted Distribution to cumulative deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Gamma	Annual Mean flows: Gamma	Annual Maximum flows: Gamma
1	0	0	0	1.1	1.10	1.13	0.06	0.09	0.11	0.00	0.00	0.00
2	0	0	0	1.1	1.10	1.13	0.06	0.09	0.11	0.00	0.00	0.00
3	0	0	0	1.1	1.10	1.13	0.06	0.09	0.11	0.00	0.00	0.00
4	0	0	0	1.1	1.10	1.13	0.06	0.09	0.11	0.00	0.00	0.00
5	0	0	138.82	1.1	1.10	2.25	0.06	0.09	0.56	0.00	0.00	0.49
6	0	31.51	826.47	1.1	2.20	3	0.06	0.55	0.67	0.00	0.51	0.68
7	0	78.36	1347.65	1.1	2.75	4.5	0.06	0.64	0.78	0.00	0.58	0.73
8	0	180.95	12503.53	1.1	3.67	9	0.06	0.73	0.89	0.00	0.66	0.97
9	21.67	883.18		2.1	5.50		0.53	0.82		0.70	0.81	
10	22.98	6498.06		2.4	11		0.59	0.91		0.70	0.97	
11	24.47			2.8			0.65			0.71		
12	27.83			3.4			0.71			0.73		
13	45.95			4.3			0.76			0.79		
14	47.87			5.7			0.82			0.80		
15	60.13			8.5			0.88			0.83		
16	329.42			17			0.94			0.98		
Coefficient of determination R <sup>2</sup> =										0.96	0.95	0.92

Table 3.3.2-4: Probability distributions of the cumulative deficits in the flows of the Niger River at Mopti, Mali

Order	Duration of deficits in Discharge (m <sup>3</sup> /s)			Return Period of duration of deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of the duration of deficits in			CDF of Fitted Distribution to the duration of deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Gamma	Annual Mean flows: Gamma	Annual Maximum flows: Gamma
1	0	0	0	1.06	1.1	1.13	0.06	0.09	0.11	0.00	0.00	0.00
2	0	0	0	1.06	1.1	1.13	0.06	0.09	0.11	0.00	0.00	0.00
3	0	0	0	1.06	1.1	1.13	0.06	0.09	0.11	0.00	0.00	0.00
4	0	0	0	1.06	1.1	1.13	0.06	0.09	0.11	0.00	0.00	0.00
5	0	0	1	1.06	1.1	2.25	0.06	0.09	0.56	0.00	0.00	0.62
6	0	1	1	1.06	2.2	2.25	0.06	0.55	0.56	0.00	0.65	0.62
7	0	1	3	1.06	2.2	4.5	0.06	0.55	0.78	0.00	0.65	0.78
8	0	1	14	1.06	2.2	9	0.06	0.55	0.89	0.00	0.65	0.96
9	1	4		2.13	5.5		0.53	0.82		0.56	0.82	
10	2	18		2.43	11		0.59	0.91		0.71	0.97	
11	2			2.43			0.59			0.71		
12	2			2.43			0.59			0.71		
13	4			4.25			0.76			0.85		
14	4			4.25			0.76			0.85		
15	4			4.25			0.76			0.85		
16	11			17			0.94			0.98		
Coefficient of determination R <sup>2</sup> ≈										0.94	0.92	0.92

Table 3.3.3.2-5: Probability distributions and return periods of run lengths of deficits in the annual flows of the Niger River, Mali

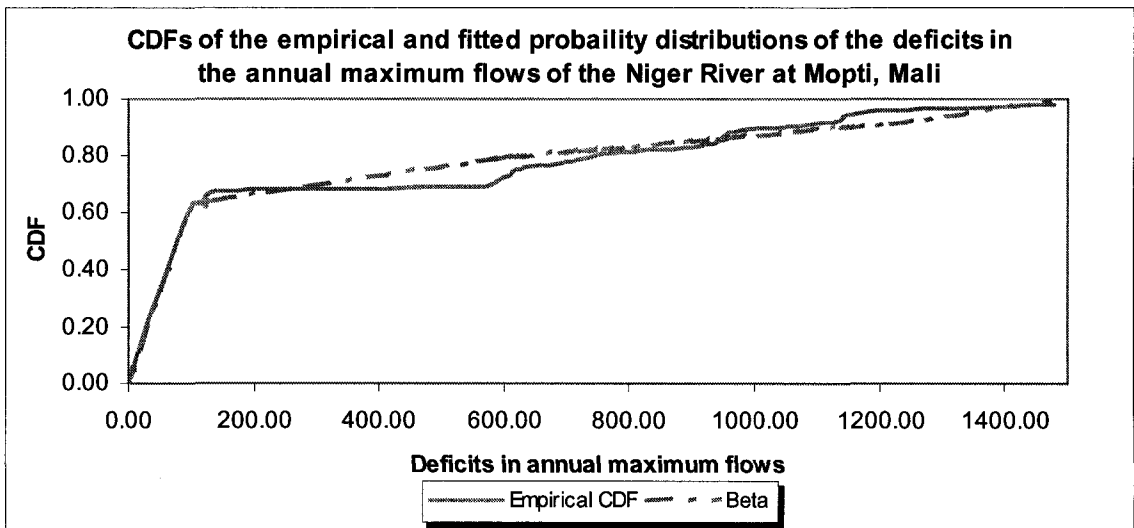
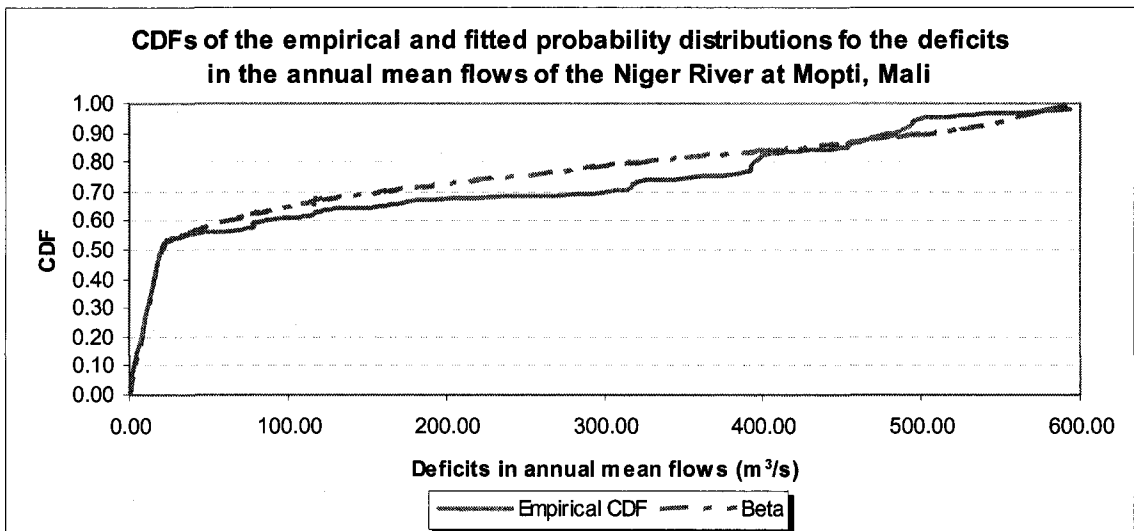
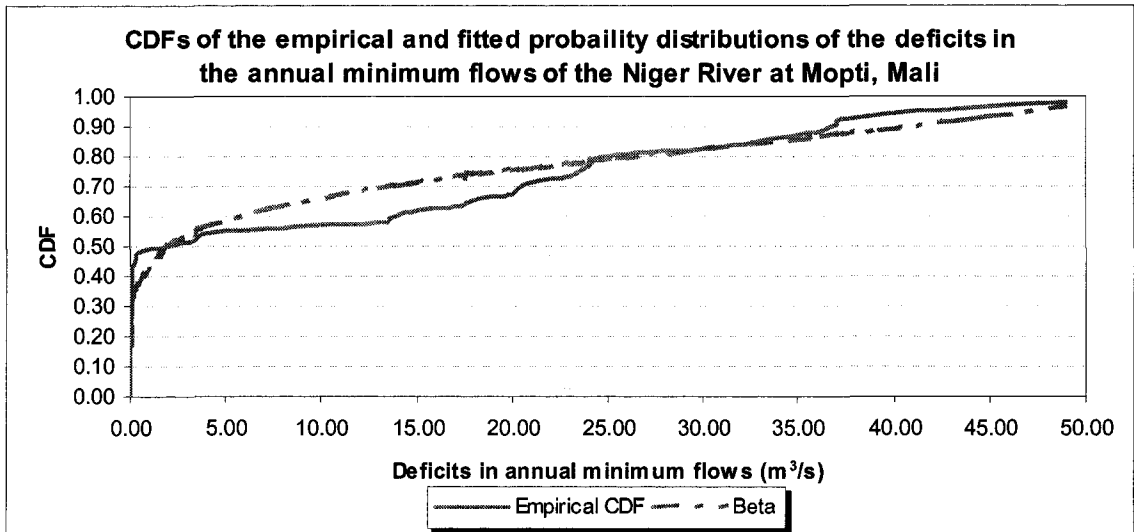


Figure 3.3.3.2-4: Probability functions of the deficits in the annual flows of the Niger River at Mopti, Mali

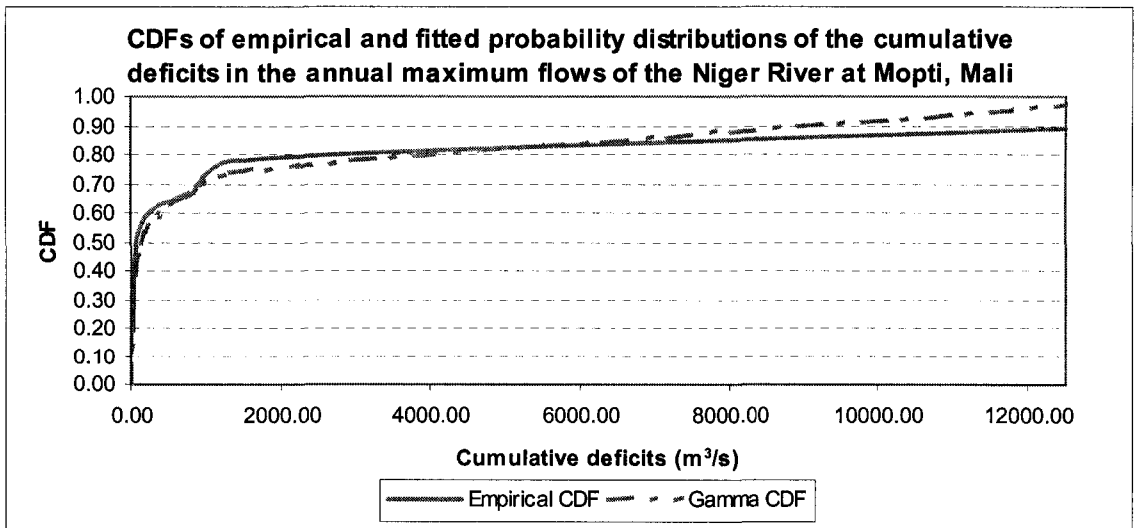
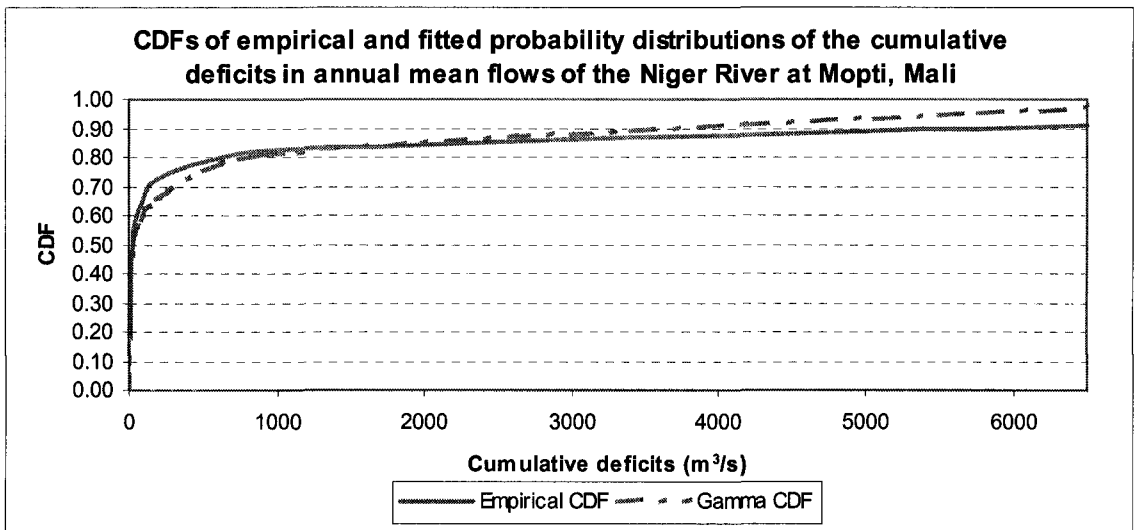
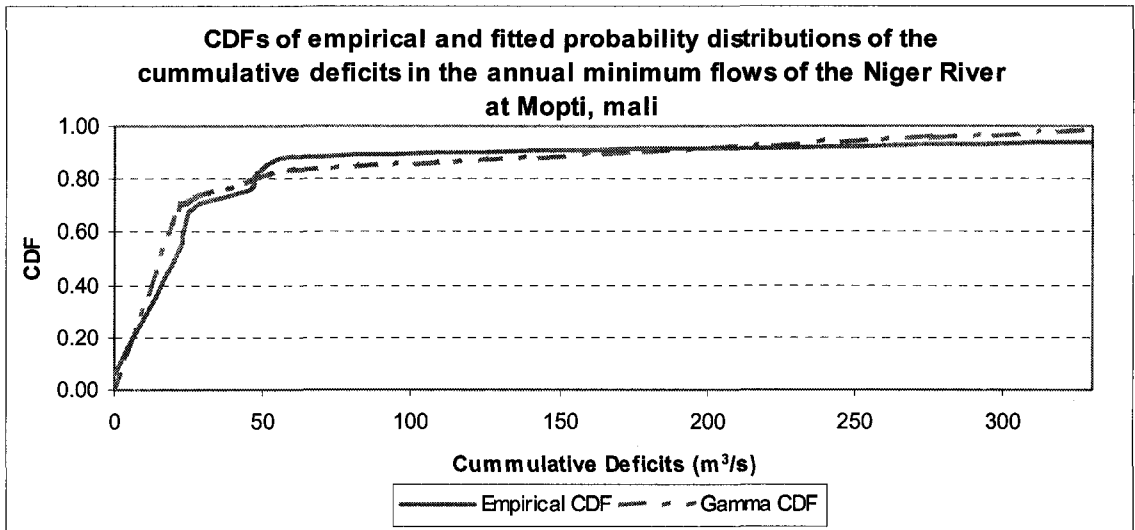


Figure 3.3.3.2-5: CDFs of probability distributions of cumulative deficits of the Niger River at Mopti, Mali

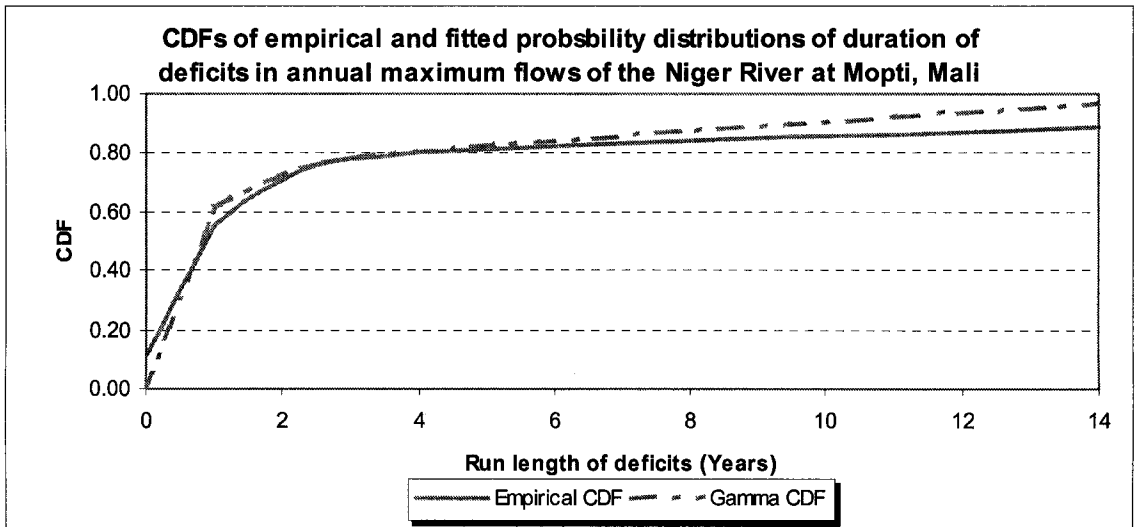
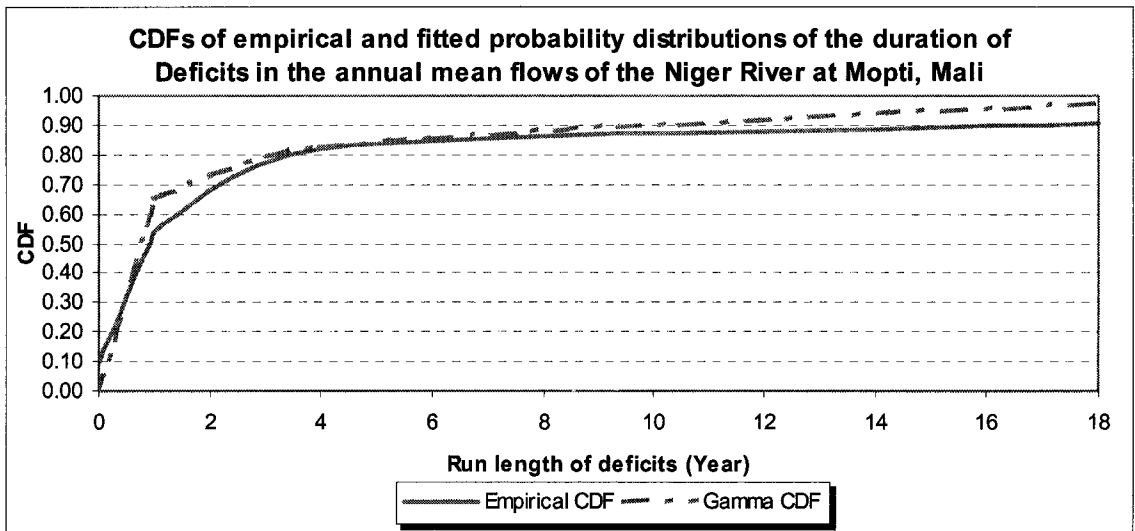
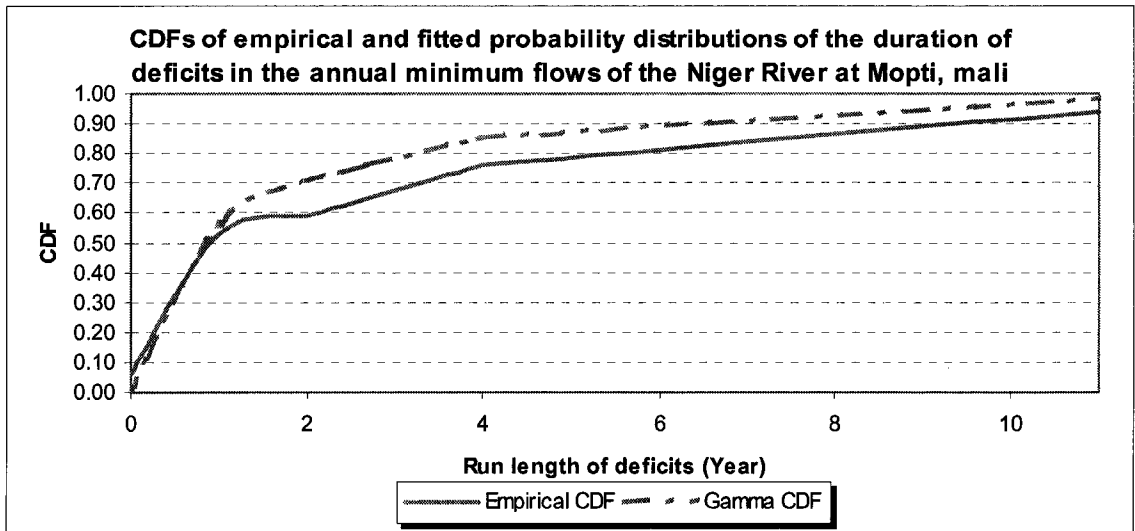


Figure 3.3.3.2-6: Probability distributions of durations of deficits in flows of the Niger River at Mopti, Mali

### 3.3.3.3. Sustainability of flows

Here again, the annual minimum flows show less sustainability than the two other flow types do.

Drought Impacts on Discharges	Performance Indicator	Annual Minimum Discharges	Annual Mean Discharges	Annual Maximum Discharges
<b>Single Year Deficits</b>	Reliability	21/51 = 0.41	21/51 = 0.51	31/51 = 0.61
	Resilience	10/30 = 0.41	26/51 = 0.51	31/51 = 0.61
	Expected Deficit (m <sup>3</sup> /s)	615.18/30 = 20.51	7672.05/25 = 306.88	14816.47/20 = 740.82
	Expected Vulnerability	0.5	0.6	0.5
	Sustainability	0.069	0.156	0.185
<b>Cumulative Deficits</b>	Reliability	8/16 = 0.5	5/10 = 0.5	4/8 = 0.5
	Resilience	8/8 = 1	5/5 = 1	4/4 = 1
	Expected Deficit (m <sup>3</sup> /s)	580.30/8 = 72.54	7672.05/5 = 1534.41	14816.47/4 = 3704.12
	Expected Vulnerability	2/8 = 0.25	1/5 = 0.20	1/4 = 0.25
	Sustainability	0.13	0.10	0.13
<b>Deficits Duration</b>	Reliability	8/16 = 0.5	5/10 = 0.5	4/8 = 0.5
	Resilience	8/8 = 1	5/5 = 1	4/4 = 1
	Expected Duration	30/8 = 3.75	25/5 = 5.00	19/4 = 4.75
	Expected Vulnerability	4/8 = 0.5	1/8 = 0.125	1/8 = 0.125
	Sustainability	0.25	0.06	0.06
<b>Relative Sustainability</b>		<b>0.444</b>	<b>0.318</b>	<b>0.372</b>

Table 3.3.3.3-1: Flow Sustainability Indices for the expected values of flow deficits and duration of deficit in the flows of the Niger River at Mopti, Mali.

Drought Impacts on Discharges	Ranking for Sustainability		
	Annual Minimum Discharges	Annual Mean Discharges	Annual Maximum Discharges
Single Year Deficits	3	2	1
Cumulative Deficits	1	3	1
Duration of Deficits	1	3	2
Overall	1	3	2

Table 3.3.3.3-2: Ranking of the flows by sustainability Indices of the Bani River at Mopti, Mali

Deficit in Annual Discharge (m <sup>3</sup> /s)			Vulnerability (Exceedence Probability)			Reliability			Resilience			Sustainability Index		
Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
0.08			0.97									0.133		
0.18			0.93									0.128		
0.28			0.90									0.124		
0.38			0.87									0.119		
1.98			0.83									0.114		
3.38	21.44		0.80	0.96								0.110	0.250	
3.78	31.51		0.77	0.92								0.105	0.239	
7.28	39.05		0.73	0.88								0.101	0.229	
13.4	77.83		0.70	0.84								0.096	0.218	
13.5	78.36		0.67	0.80								0.092	0.208	
14.3	114.29	98.82	0.63	0.76	0.95							0.087	0.198	0.351
17.2	122.71	118.82	0.60	0.72	0.90							0.082	0.187	0.333
17.9	160.89	118.82	0.57	0.68	0.90							0.078	0.177	0.333
19.9	180.95	138.82	0.53	0.64	0.80							0.073	0.166	0.296
20.2	291.94	558.82	0.50	0.60	0.75	0.41						0.069	0.156	0.277
21.0	316.05	588.82	0.47	0.56	0.70	0.51						0.064	0.146	0.259
22.9	320.25	608.82	0.43	0.52	0.65	0.61						0.059	0.135	0.240
22.9	352.58	618.82	0.43	0.48	0.60				0.33	0.51	0.61	0.059	0.125	0.222
23.9	390.70	688.82	0.37	0.44	0.55							0.050	0.114	0.203
24.2	392.28	718.82	0.33	0.40	0.50							0.046	0.104	0.185
25.4	397.22	758.82	0.30	0.36	0.45							0.041	0.094	0.166
30.5	405.21	898.82	0.27	0.32	0.40							0.037	0.083	0.148
32.5	453.80	938.82	0.23	0.28	0.35							0.032	0.073	0.129
34.6	455.73	948.82	0.20	0.24	0.30							0.027	0.062	0.111
36.2	470.31	958.82	0.17	0.20	0.25							0.023	0.052	0.092
36.9	486.41	1068.8	0.13	0.16	0.20							0.018	0.042	0.074
37.0	493.91	1138.8	0.10	0.12	0.15							0.014	0.031	0.055
39.2	498.66	1148.8	0.07	0.08	0.10							0.009	0.021	0.037
43.6	526.84	1218.8	0.03	0.04	0.05							0.005	0.010	0.018
48.9	593.15	1478.8	0.00	0.00	0.00							0.000	0.000	0.000

Table 3.3.3.3-3: Sustainability Indices for different deficit levels in the flows of the Niger River at Mopti, Mali

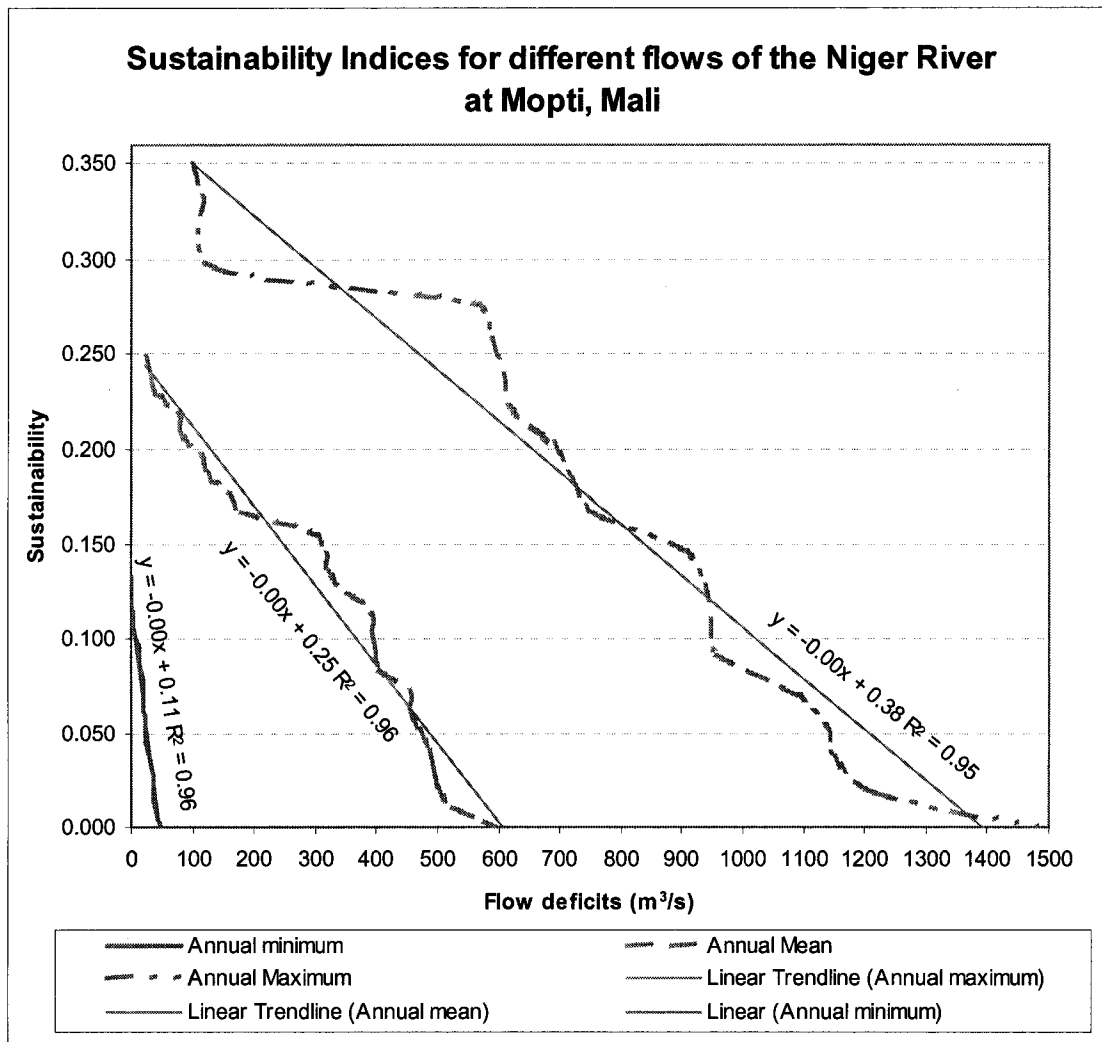


Figure 3.3.3.3-1: Sustainability Indices of the different flow types of the Niger River at Mopti, Mali

Like the annual minimum flows at Koulikoro gaging station, those of Mopti gaging station too, have a sustainability decreasing at steep rate.

### 3.3.4. The Issa Ber at Dire, Mali

The Issa Ber is one of the braided channels draining waters of the Niger River through the Inner Delta at the exit of which the city of Dire is located; the

gaging station has a 71-year long data record. Here the long-term average values serving as threshold are 42.92 m<sup>3</sup>/s for the annual minimum flows, 978.42 m<sup>3</sup>/s for the annual mean flows, and 2062.82 m<sup>3</sup>/s for the annual maximum flows.

As shown in Figure 3.3.4-1, the annual mean and maximum flows at this gaging station are more or less steady. The same trend can be observed in the annual minimum flows, except for especially wet years with sharp increases.

#### **3.3.4.1. Characteristics of flow deficits**

The three flow-types of the Issa Ber exhibit to certain extent the same patterns of flow deficits observed at other gaging stations. However, in contrast, here the excesses or deficits are sharper in the annual minimum flows than in the mean and maximum flows; they range from 86% deficit in 1978 to 400% excess in 1958. From the graphs of Figures 3.3.4.2-1 and 3.3.4.2-2, it can also be observed that the periods of deficits in the annual minimum flows are much longer than those of the deficits in the annual mean and maximum discharges.

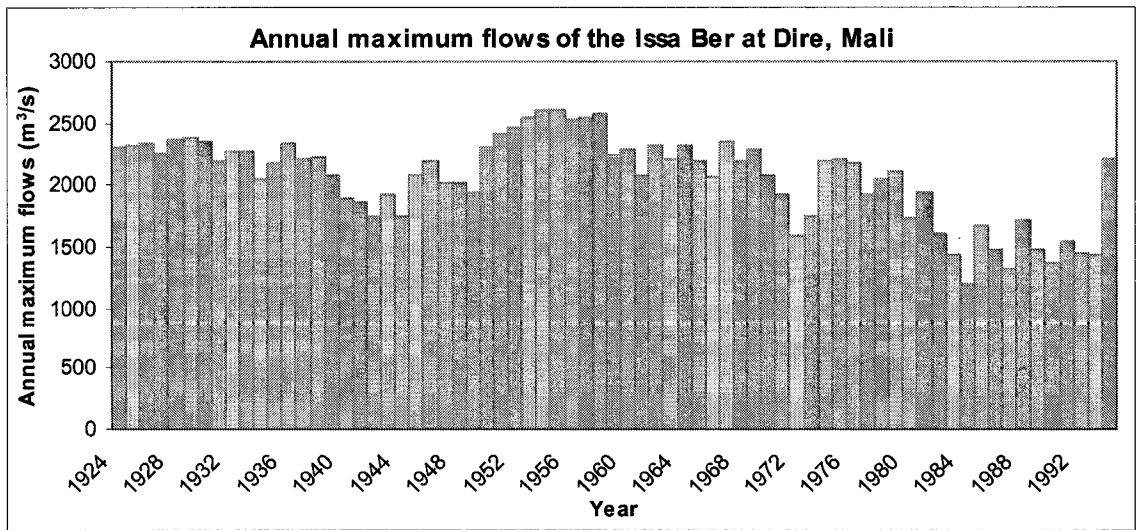
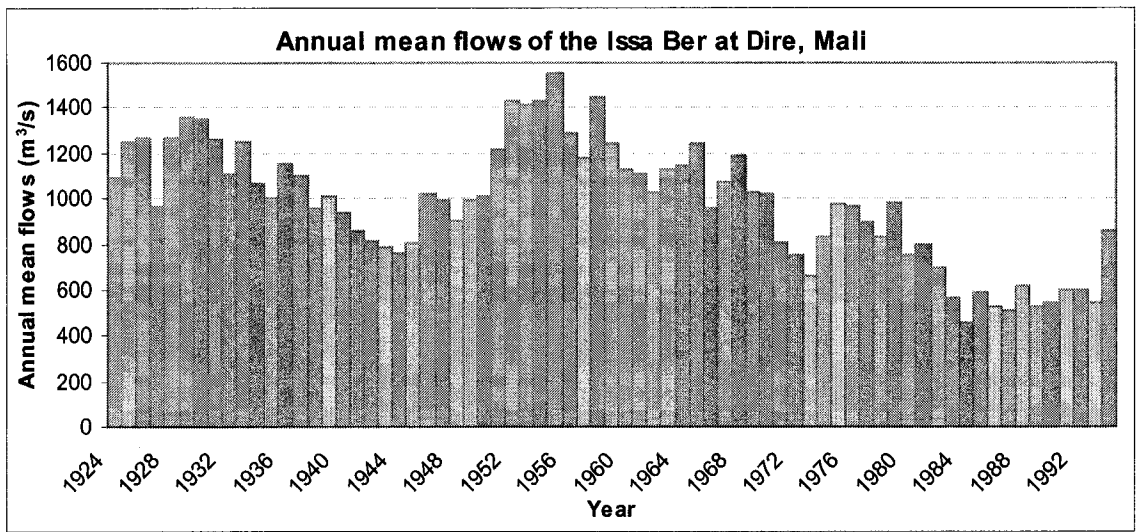
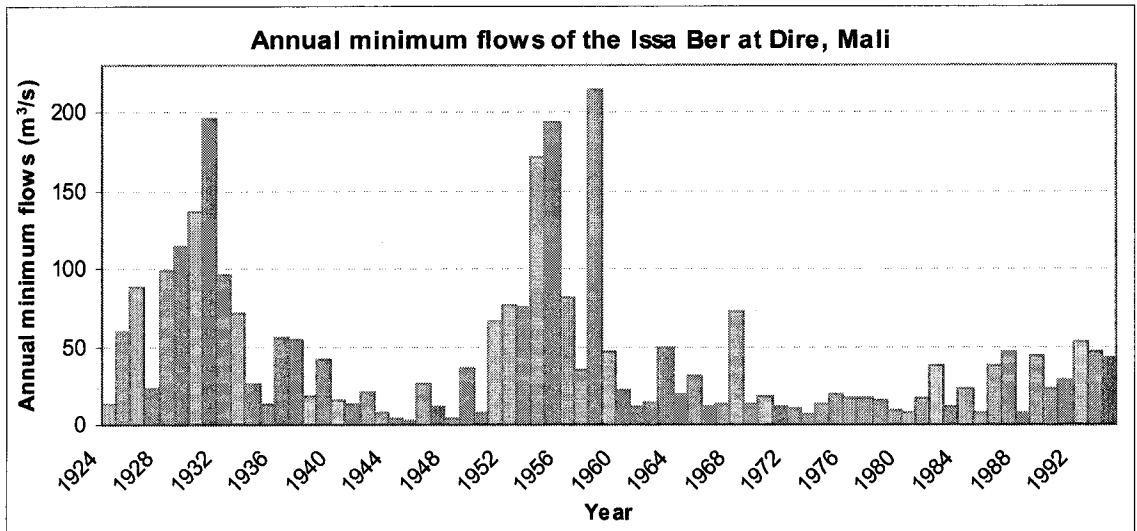


Figure 3.3.4-1: Annual flows of the Issa Ber at Dire, Mali

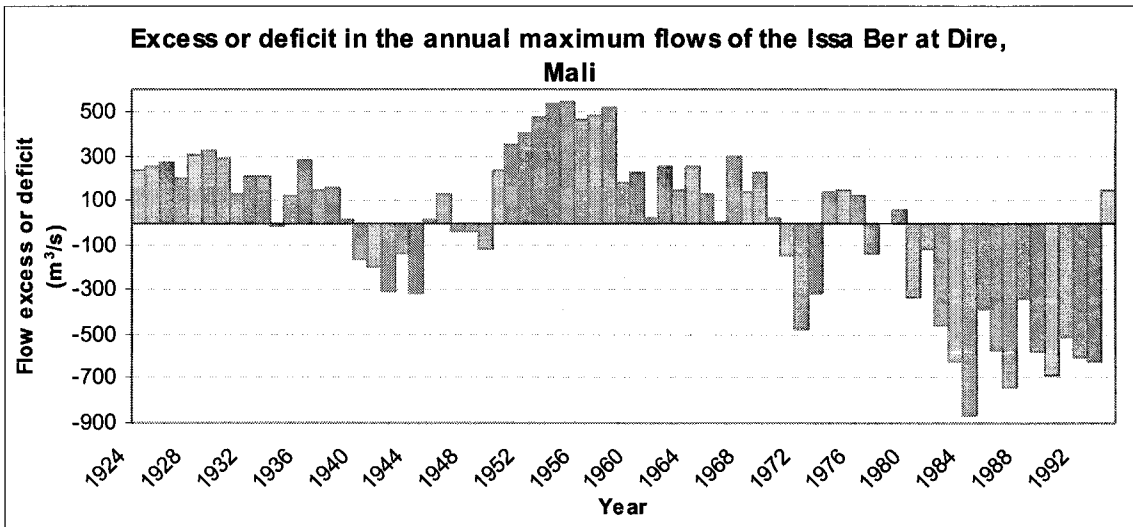
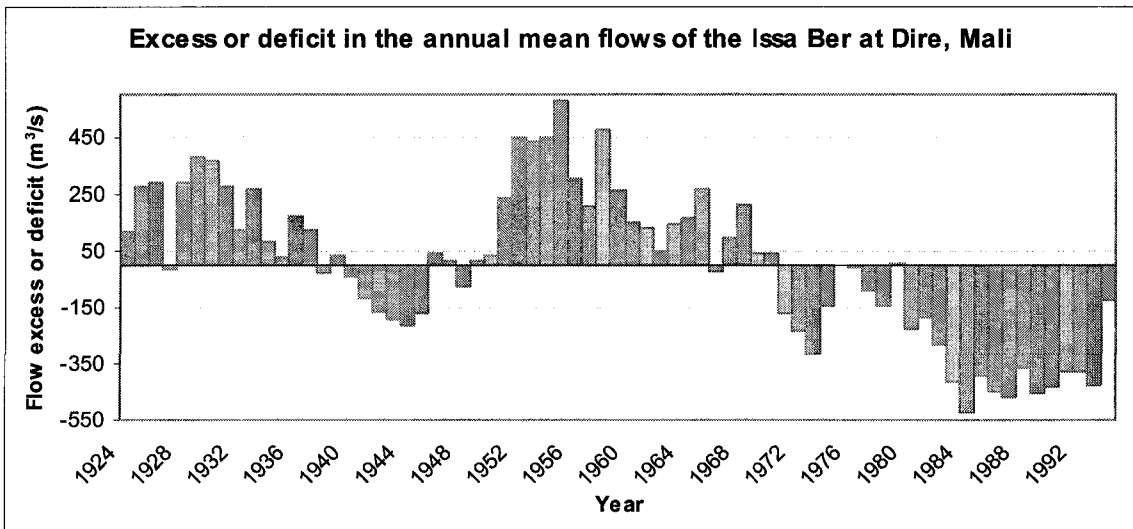
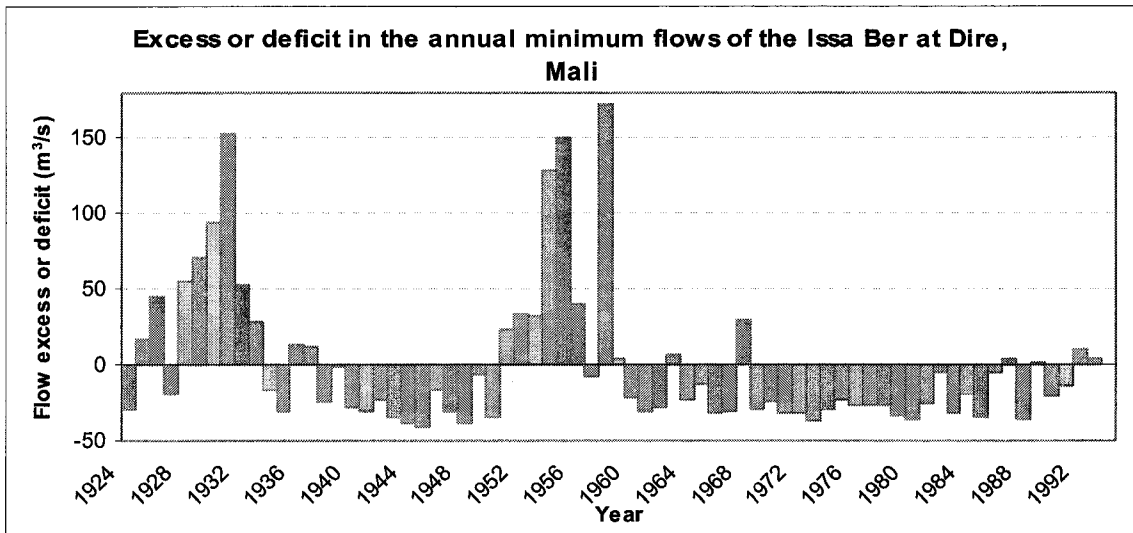


Figure 3.3.4.1-1: Flow excess or deficits of the Issa Ber at Dire, Mali

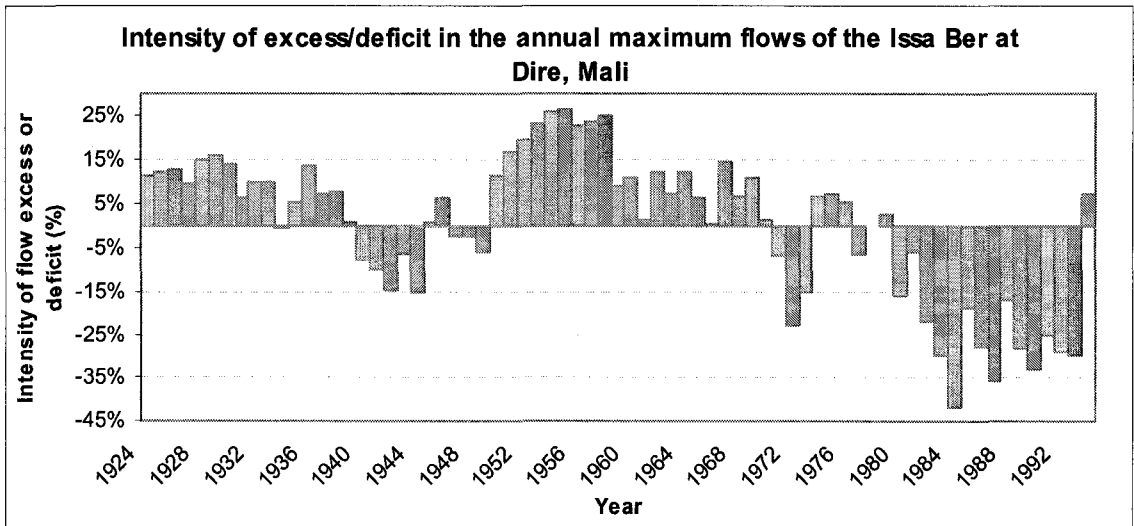
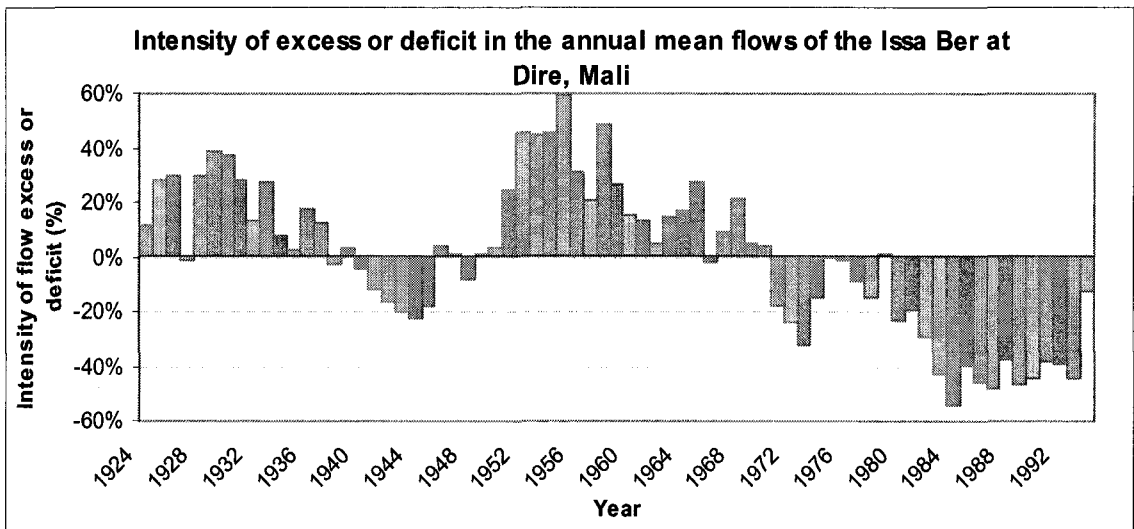
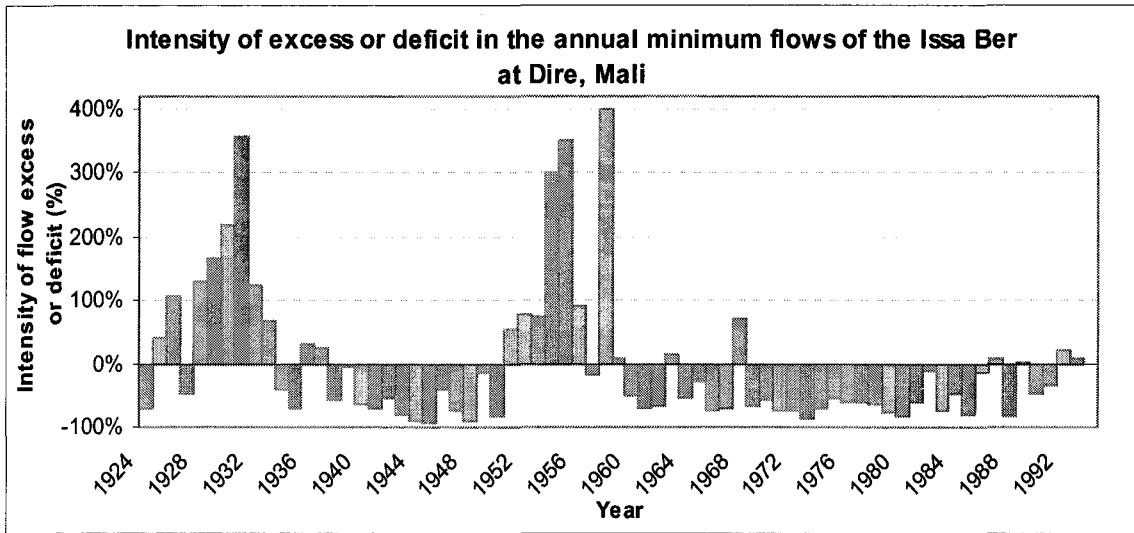


Figure 3.3.4.1-2: Intensity of excess or deficit in flows of the Issa Ber at Dire, Mali

From the graphs of Figures 3.3.4.2-1 and 3.3.4-2, the deficits data were used to generate the deficits sequences, timing, run length and ratio as shown in Table 3.3.4.2-1.

Discharge Type	Deficits sequence	Timing		Run length (Year)	Intensity (%)	
		Start (Year)	End (Year)		Average	Maximum
Annual minimum flow	1	1924	1924	1	70	70
	2	1927	1927	1	46	46
	3	1934	1935	2	55	71
	4	1938	1950	13	63	94
	5	1957	1957	1	18	18
	6	1960	1962	3	63	72
	7	1964	1986	23	52	86
	8	1988	1988	1	82	82
	9	1990	1991	2	40	40
	10	1994	1994	1	1	1
<b>Maximum</b>				<b>23</b>	<b>82%</b>	<b>94%</b>
Average annual mean flow	1	1927	1927	1	1	1
	2	1938	1938	1	38	38
	3	1940	1945	6	15	22
	4	1971	1974	4	22	32
	5	1976	1978	3	12.5	15
	6	1980	1994	15	37	54
<b>Maximum</b>				<b>15</b>	<b>38%</b>	<b>54%</b>
Annual maximum flow	1	1934	1934	1	1	1
	2	1940	1944	5	11	15
	3	1971	1973	3	15	32
	4	1977	1977	1	6	6
	5	1980	1993	14	26	42
<b>Maximum</b>				<b>14</b>	<b>26%</b>	<b>42%</b>

Table 3.3.4.1-1: Intensity of deficits in the flows of the Issa Ber at Dire, Mali

In both terms of average and maximum intensity of deficits, the annual minimum flows more affected, compared to the mean and maximum flows.

### 3.3.4.2. Statistics and distribution of the deficits, cumulative deficits and run lengths

The statistics of the deficits data are given in the Table 3.3.4.2-1, below.

Statistics	Deficits in annual flows		
	Minimum discharge	Mean Discharge	Maximum Discharge
Mean	16.63	107.61	138.58
Standard Error	1.73	18.86	27.35
Median	19.72	0	0
Standard Deviation	14.58	158.95	230.44
Sample Variance	212.59	25264.06	53102.56
Kurtosis	-1.69	0.18	1.25
Skewness	0.00	1.26	1.57
Coefficient of variation	0.88	1.48	1.66
Range	40.38	524.37	862.82
Minimum	0	0	0
Maximum	40.38	524.3668	862.82
	Cumulative deficits		
Mean	62.13	545.72	756.84
Standard Error	30.37	393.13	566.50
Median	0.52	6.25	0
Standard Deviation	132.36	1470.95	2042.55
Sample Variance	17520.30	2163694.60	4172001.44
Kurtosis	5.81	11.95	11.89
Skewness	2.53	3.39	3.41
Coefficient of variation	2.13	2.70	2.7
Range	478.06	5500.92	7439.44
Minimum	0	0	0
Maximum	478.06	5500.92	7439.44
	Run length		
Mean	2	2.36	2.15
Standard Error	0.83	1.17	1.09
Median	1	0.5	0
Standard Deviation	3.61	4.40	3.91
Sample Variance	13	19.32	15.31
Kurtosis	4.41	5.00	7.79
Skewness	2.23	2.27	2.66
Coefficient of variation	1.80	1.86	1.82
Range	13	15	14
Minimum	0	0	0
Maximum	13	15	14

Table 3.3.4.2-1: Statistics of deficits in the flows of the Issa Ber at Dire, Mali

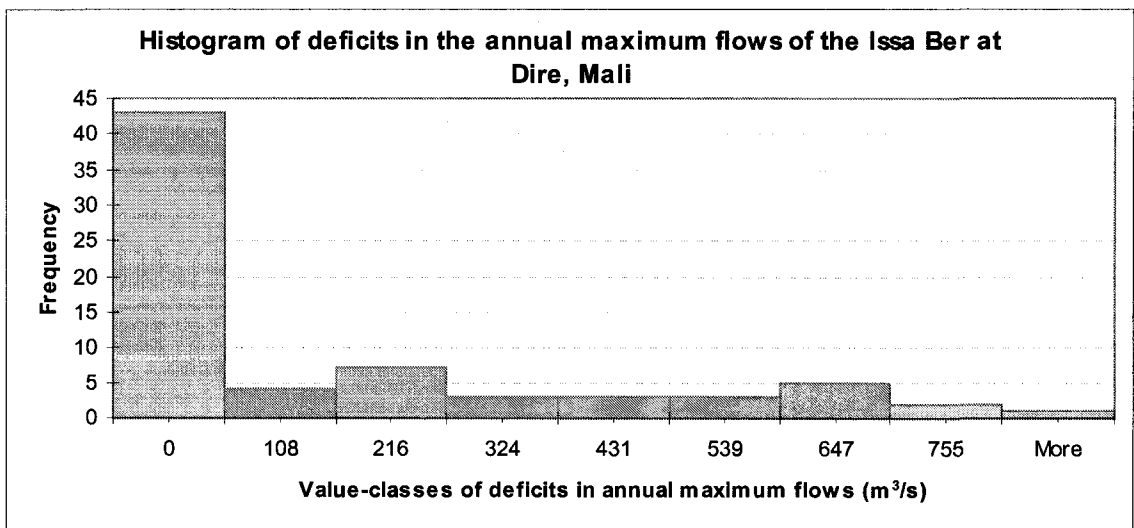
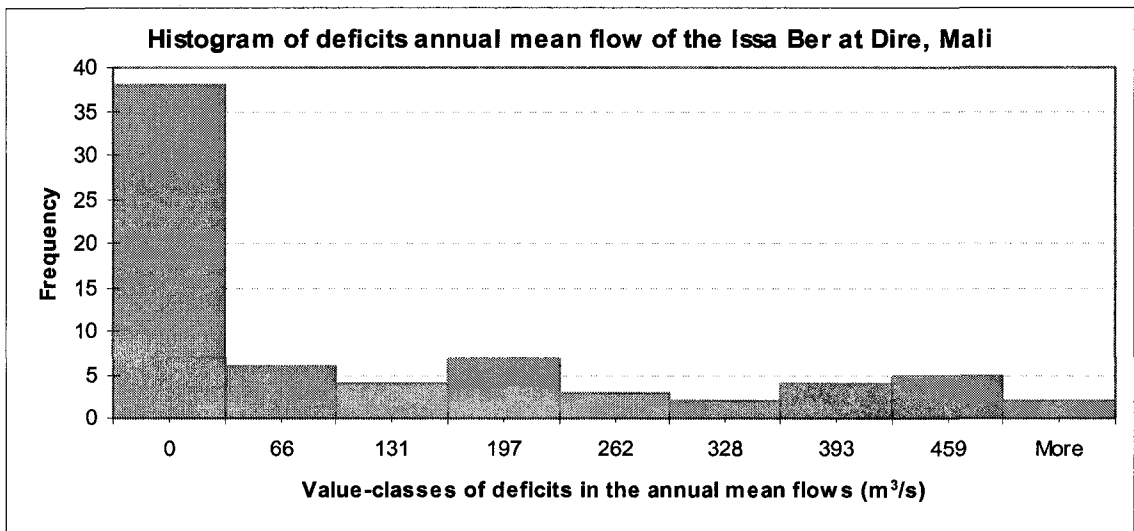
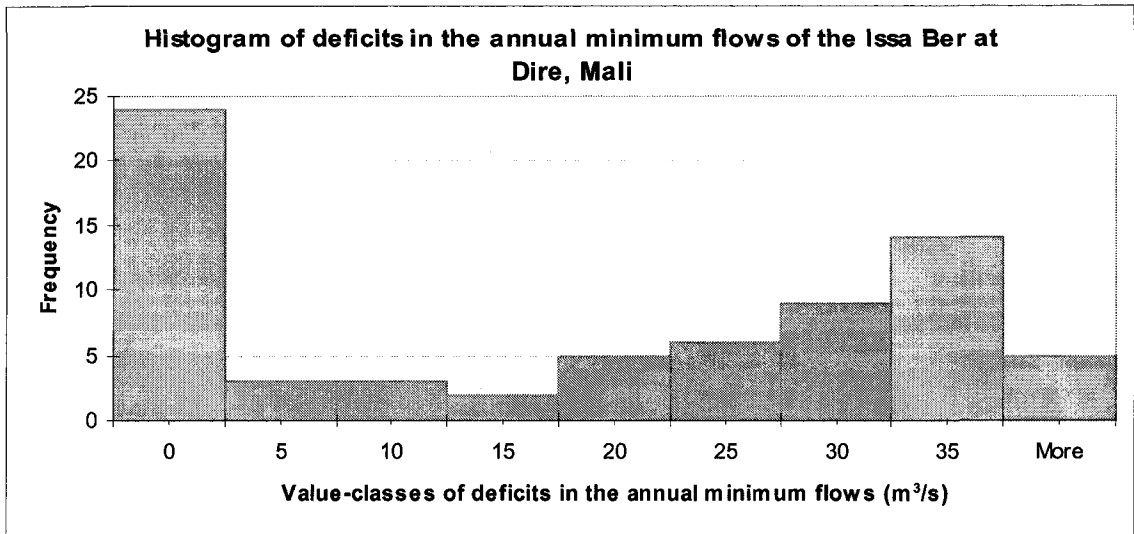


Figure 3.3.4.2-1: Histograms of deficits in the flows of the Issa Ber at Dire, Mali

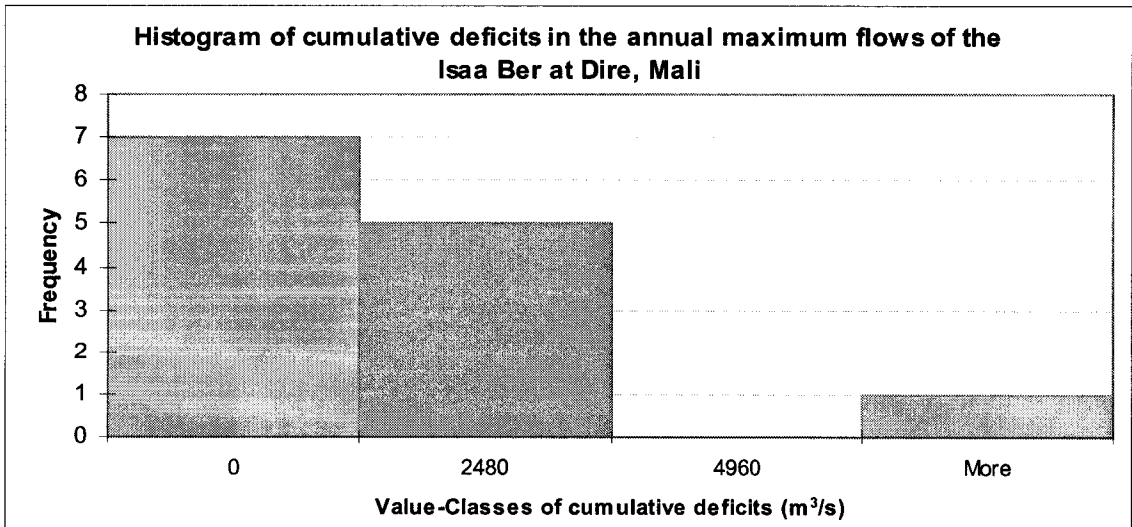
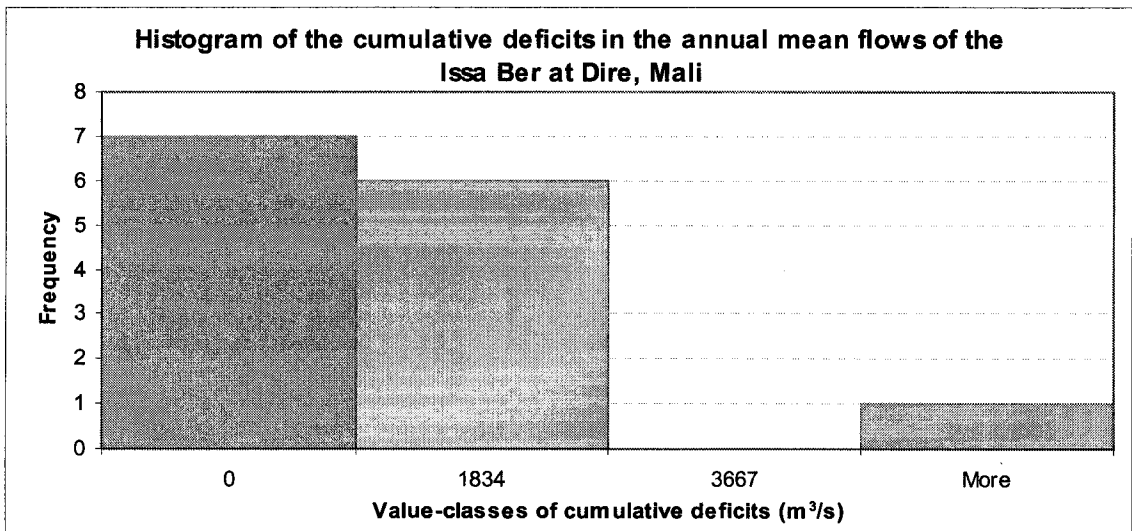
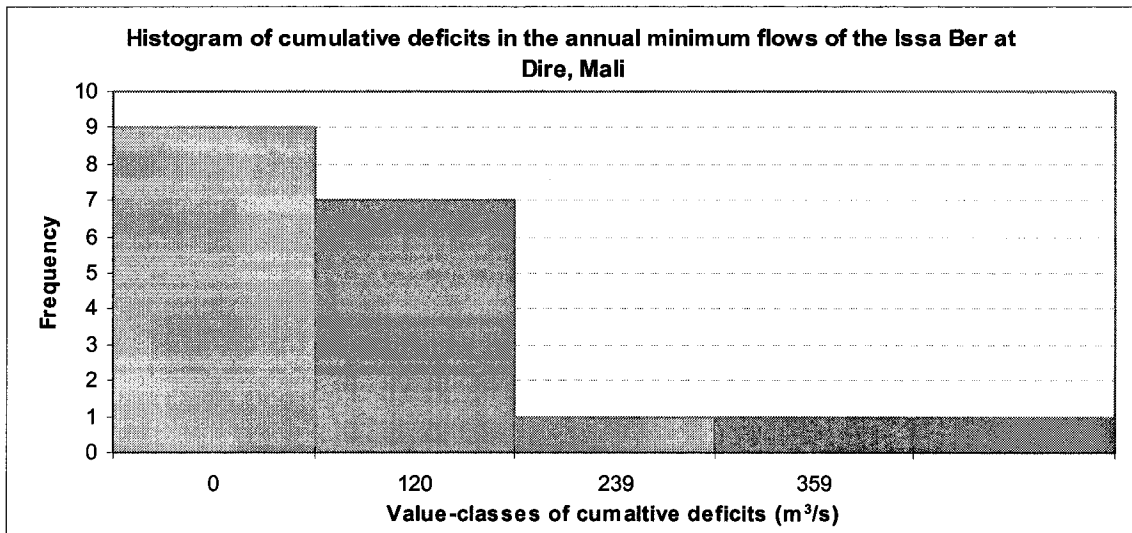


Figure 3.3.4.2-2: Histograms of cumulative deficit in the flows of the Issa Ber at Dire, Mali

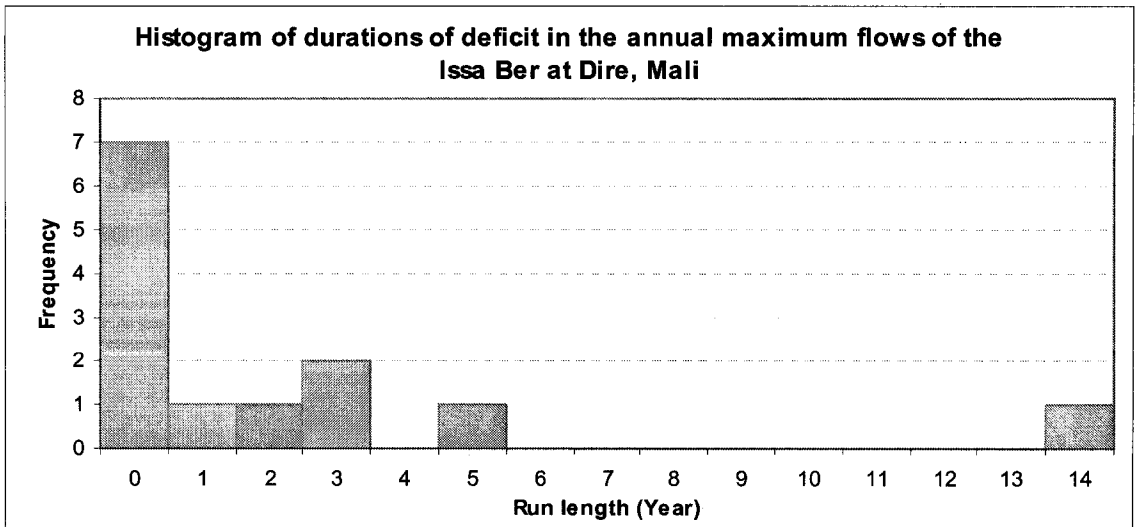
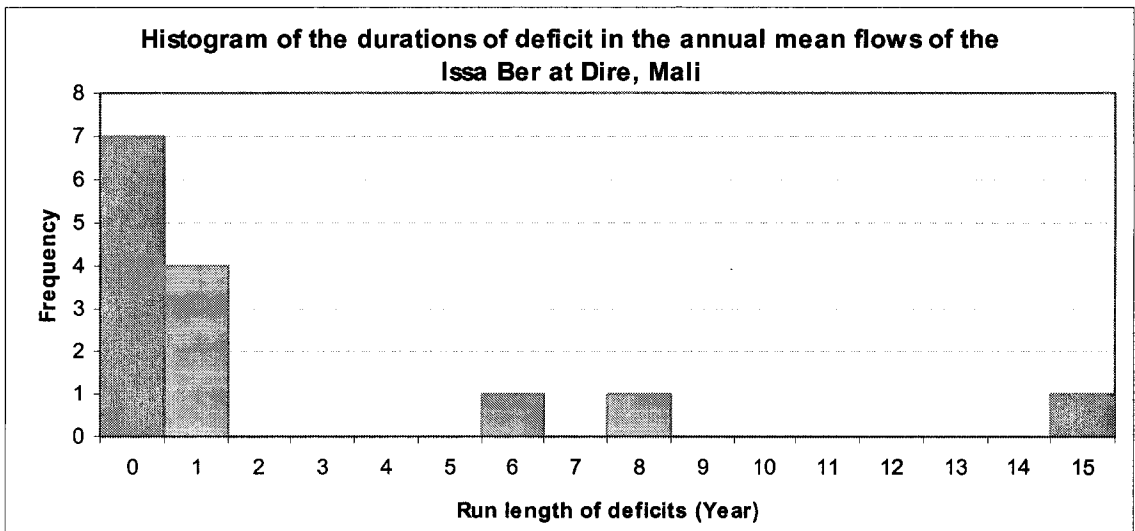
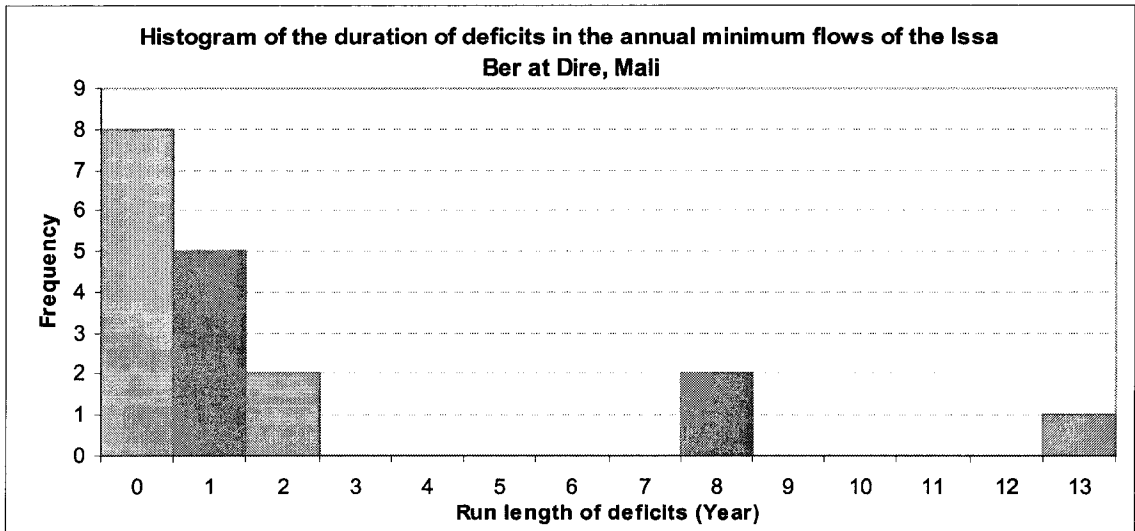


Figure 3.3.4.2-3: Histograms of run length of deficits in flows of the Issa Ber at Dire, Mali

The beta probability distribution function was fitted to the data of the deficits in the flows of the Issa Ber at Dire; the initial moment estimators of the parameters were optimized. The gamma probability distribution function was fitted to the cumulative deficits and to the run lengths.

Fitted probability function		Deficits in annual		
		Minimum discharge	Mean Discharge	Maximum Discharge
Type		Beta	Beta	Beta
Parameters Estimators	$\hat{\alpha} =$	0.40	0.14	0.13
	$\hat{\beta} =$	0.56	0.56	0.63
Coefficient of determination		0.97	0.99	0.99
		Cumulative deficits		
Type		Gamma	Gamma	Gamma
Parameters Estimators	$\hat{\alpha} =$	0.27	0.23	0.09
	$\hat{\beta} =$	341.19	10.85	8571.40
Coefficient of determination		0.91	0.97	0.96
		Run length of deficits		
Type		Gamma	Gamma	Gamma
Parameters Estimators	$\hat{\alpha} =$	0.41	0.23	0.22
	$\hat{\beta} =$	7.14	10.45	9.68
Coefficient of determination		0.97	0.96	0.95

Table 3.3.4.2-2: Parameters of probability distribution functions fitted to the deficits in the annual flows of the Issa Ber at Dire, Mali

Order	Volume of deficits in Annual Discharge (m <sup>3</sup> /s)			Return Period of deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of deficits in			CDF of Fitted Distribution to deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Beta	Annual Mean flows: Beta	Annual Maximum flows: Beta
1	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
2	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
3	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
4	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
5	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
6	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
7	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
8	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
9	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
10	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
11	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
12	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
13	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
14	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
15	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
16	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
17	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
18	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
19	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
20	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
21	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
22	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
23	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
24	0.00	0.00	0.00	1.01	1.01	1.01	0.01	0.01	0.01	0	0.00	0.00
25	0.52	0.00	0.00	1.53	1.01	1.01	0.35	0.01	0.01	0.13	0.00	0.00
26	1.42	0.00	0.00	1.57	1.01	1.01	0.36	0.01	0.01	0.19	0.00	0.00
27	4.62	0.00	0.00	1.60	1.01	1.01	0.38	0.01	0.01	0.31	0.00	0.00
28	5.52	0.00	0.00	1.64	1.01	1.01	0.39	0.01	0.01	0.33	0.00	0.00
29	6.72	0.00	0.00	1.67	1.01	1.01	0.40	0.01	0.01	0.36	0.00	0.00
30	7.62	0.00	0.00	1.71	1.01	1.01	0.42	0.01	0.01	0.38	0.00	0.00
31	12.22	0.00	0.00	1.76	1.01	1.01	0.43	0.01	0.01	0.47	0.00	0.00
32	14.22	0.00	0.00	1.80	1.01	1.01	0.44	0.01	0.01	0.50	0.00	0.00
33	16.82	0.00	0.00	1.85	1.01	1.01	0.46	0.01	0.01	0.54	0.00	0.00
34	17.22	0.00	0.00	1.89	1.01	1.01	0.47	0.01	0.01	0.54	0.00	0.00
35	19.62	0.00	0.00	1.95	1.01	1.01	0.49	0.01	0.01	0.58	0.00	0.00
36	19.72	0.00	0.00	2.00	1.01	1.01	0.50	0.01	0.01	0.58	0.00	0.00
37	19.82	0.00	0.00	2.06	1.01	1.01	0.51	0.01	0.01	0.59	0.00	0.00
38	21.22	0.00	0.00	2.12	1.01	1.01	0.53	0.01	0.01	0.61	0.00	0.00
39	22.72	1.27	0.00	2.18	2.18	1.01	0.54	0.54	0.01	0.63	0.37	0.00
40	23.22	8.88	0.00	2.25	2.25	1.01	0.56	0.56	0.01	0.64	0.49	0.00
41	23.32	12.50	0.00	2.32	2.32	1.01	0.57	0.57	0.01	0.64	0.51	0.00
42	24.42	19.13	0.00	2.40	2.40	1.01	0.58	0.58	0.01	0.65	0.55	0.00
43	24.92	25.20	0.00	2.48	2.48	1.01	0.60	0.60	0.01	0.66	0.57	0.00
44	26.02	38.20	2.82	2.57	2.57	2.57	0.61	0.61	0.61	0.68	0.60	0.43

Table 3.3.4.2-3: Probability distributions of the deficits in the flows of the Issa Ber at Dire, Mali

Order	Volume of deficits in Annual Discharge (m <sup>3</sup> /s)			Return Period of deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of deficits in			CDF of Fitted Distribution to deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Beta	Annual Mean flows: Beta	Annual Maximum flows: Beta
45	26.32	77.84	12.82	2.67	2.67	2.67	0.63	0.63	0.63	0.68	0.67	0.52
46	26.42	86.96	42.82	2.77	2.77	2.77	0.64	0.64	0.64	0.68	0.68	0.61
47	27.32	116.88	42.82	2.88	2.88	2.77	0.65	0.65	0.64	0.69	0.71	0.61
48	27.82	123.35	122.82	3.00	3.00	3.00	0.67	0.67	0.67	0.70	0.72	0.70
49	28.52	143.16	122.82	3.13	3.13	3.00	0.68	0.68	0.67	0.71	0.74	0.70
50	29.32	143.54	132.82	3.27	3.27	3.27	0.69	0.69	0.69	0.72	0.74	0.71
51	29.52	162.44	132.82	3.43	3.43	3.27	0.71	0.71	0.69	0.73	0.75	0.71
52	29.92	172.40	142.82	3.60	3.60	3.60	0.72	0.72	0.72	0.73	0.76	0.72
53	30.32	173.68	162.82	3.79	3.79	3.79	0.74	0.74	0.74	0.74	0.76	0.73
54	30.32	185.13	202.82	3.79	4.00	4.00	0.74	0.75	0.75	0.74	0.77	0.76
55	30.42	194.08	302.82	4.24	4.24	4.24	0.76	0.76	0.76	0.74	0.78	0.80
56	30.82	215.59	312.82	4.50	4.50	4.50	0.78	0.78	0.78	0.75	0.79	0.81
57	31.22	228.82	312.82	4.80	4.80	4.50	0.79	0.79	0.78	0.75	0.80	0.81
58	31.42	231.94	332.82	5.14	5.14	5.14	0.81	0.81	0.81	0.76	0.80	0.81
59	31.72	283.86	342.82	5.54	5.54	5.54	0.82	0.82	0.82	0.76	0.83	0.82
60	31.82	315.44	382.82	6.00	6.00	6.00	0.83	0.83	0.83	0.76	0.85	0.83
61	32.12	365.34	452.82	6.55	6.55	6.55	0.85	0.85	0.85	0.77	0.87	0.85
62	33.44	375.61	472.82	7.20	7.20	7.20	0.86	0.86	0.86	0.79	0.88	0.86
63	34.51	381.03	512.82	8.00	8.00	8.00	0.88	0.88	0.88	0.81	0.88	0.87
64	34.63	389.01	572.82	9.00	9.00	9.00	0.89	0.89	0.89	0.81	0.89	0.89
65	35.20	414.15	582.82	10.29	10.29	10.29	0.90	0.90	0.90	0.82	0.90	0.89
66	35.22	428.99	602.82	12.00	12.00	12.00	0.92	0.92	0.92	0.82	0.91	0.90
67	35.55	430.67	622.82	14.40	14.40	14.40	0.93	0.93	0.93	0.83	0.91	0.91
68	36.79	450.00	622.82	18.00	18.00	14.40	0.94	0.94	0.93	0.85	0.92	0.91
69	38.39	454.16	682.82	24.00	24.00	24.00	0.96	0.96	0.96	0.89	0.93	0.92
70	38.88	466.44	742.82	36.00	36.00	36.00	0.97	0.97	0.97	0.90	0.93	0.94
71	40.38	524.37	862.82	72.00	72.00	72.00	0.99	0.99	0.99	0.95	1.00	1.00
Coefficient of determination R <sup>2</sup> =										0.97	0.99	0.99

Table 3.3.4.2-3 (continued): CDFs of probability distributions of the deficits in the flows of the Issa Ber at Dire, Mali

Order	Volume of deficits cumulative deficit in Discharge (m <sup>3</sup> /s)			Return Period of cumulative deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of cumulative deficits in			CDF of Fitted Distribution to cumulative deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Gamma	Annual Mean flows: Gamma	Annual Maximum flows: Gamma
1	0	0.00	0.00	1.05	1.07	1.1	0.05	0.07	0.07	0.00	0	0.00
2	0	0.00	0.00	1.05	1.07	1.1	0.05	0.07	0.07	0.00	0	0.00
3	0	0.00	0.00	1.05	1.07	1.1	0.05	0.07	0.07	0.00	0	0.00
4	0	0.00	0.00	1.05	1.07	1.1	0.05	0.07	0.07	0.00	0	0.00
5	0	0.00	0.00	1.05	1.07	1.1	0.05	0.07	0.07	0.00	0	0.00
6	0	0.00	0.00	1.05	1.07	1.1	0.05	0.07	0.07	0.00	0	0.00
7	0	0.00	0.00	1.05	1.07	1.1	0.05	0.07	0.07	0.00	0	0.00
8	0	12.50	12.82	1.05	2.14	2.3	0.05	0.53	0.57	0.00	0.58	0.59
9	0	19.13	135.63	1.05	2.5	2.8	0.05	0.60	0.64	0.00	0.60	0.72
10	0.52	25.20	208.45	2.00	3	3.5	0.50	0.67	0.71	0.20	0.62	0.75
11	7.62	77.84	928.45	2.22	3.75	4.7	0.55	0.73	0.79	0.40	0.69	0.84
12	19.72	899.58	1114.08	2.50	5	7	0.60	0.80	0.86	0.51	0.86	0.86
13	29.92	1104.87	7439.44	2.86	7.5	14	0.65	0.87	0.93	0.57	0.88	0.97
14	34.05	5500.92		3.33	15		0.70	0.93		0.59	0.97	
15	35.22			4.00			0.75			0.59		
16	47.15			5.00			0.80			0.64		
17	178.27			6.67			0.85			0.84		
18	349.87			10.00			0.90			0.93		
19	478.06			20.00			0.95			0.96		
Coefficient of determination R <sup>2</sup> =										0.91	0.97	0.97

Table 3.3.4.2-4: Probability distributions of cumulative deficits in flows of the Issa Ber at Dire, Mali

Order	Duration of deficits in Discharge (m <sup>3</sup> /s)			Return Period of duration of deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of the duration of deficits in			CDF of Fitted Distribution to the duration of deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Gamma	Annual Mean flows: Gamma	Annual Maximum flows: Gamma
1	0	0	0	1.05	1.07	1.1	0.05	0.07	0.07	0.00	0	0.00
2	0	0	0	1.05	1.07	1.1	0.05	0.07	0.07	0.00	0	0.00
3	0	0	0	1.05	1.07	1.1	0.05	0.07	0.07	0.00	0	0.00
4	0	0	0	1.05	1.07	1.1	0.05	0.07	0.07	0.00	0	0.00
5	0	0	0	1.05	1.07	1.1	0.05	0.07	0.07	0.00	0	0.00
6	0	0	0	1.05	1.07	1.1	0.05	0.07	0.07	0.00	0	0.00
7	0	0	0	1.05	1.07	1.1	0.05	0.07	0.07	0.00	0	0.00
8	0	1	1	1.05	2.14	2.3	0.05	0.53	0.57	0.00	0.62	0.65
9	0	1	2	1.05	2.14	2.8	0.05	0.53	0.64	0.00	0.62	0.74
10	1	1	3	2	2.14	3.5	0.5	0.53	0.71	0.48	0.62	0.80
11	1	1	3	2	2.14	3.5	0.5	0.53	0.71	0.48	0.62	0.80
12	1	6	5	2	5.00	7.0	0.5	0.80	0.86	0.48	0.87	0.87
13	1	8	14	2	7.50	14.0	0.5	0.87	0.93	0.48	0.91	0.97
14	1	15		2	15		0.5	0.93		0.48	0.96	
15	2			4			0.75			0.62		
16	2			4			0.75			0.62		
17	8			6.67			0.85			0.90		
18	8			6.67			0.85			0.90		
19	13			20			0.95			0.96		
Coefficient of determination R <sup>2</sup> =										0.97	0.96	0.95

Table 3.3.4.2-5: Probability distributions of the durations of deficits in the flows of the Issa Ber at Dire, Mali

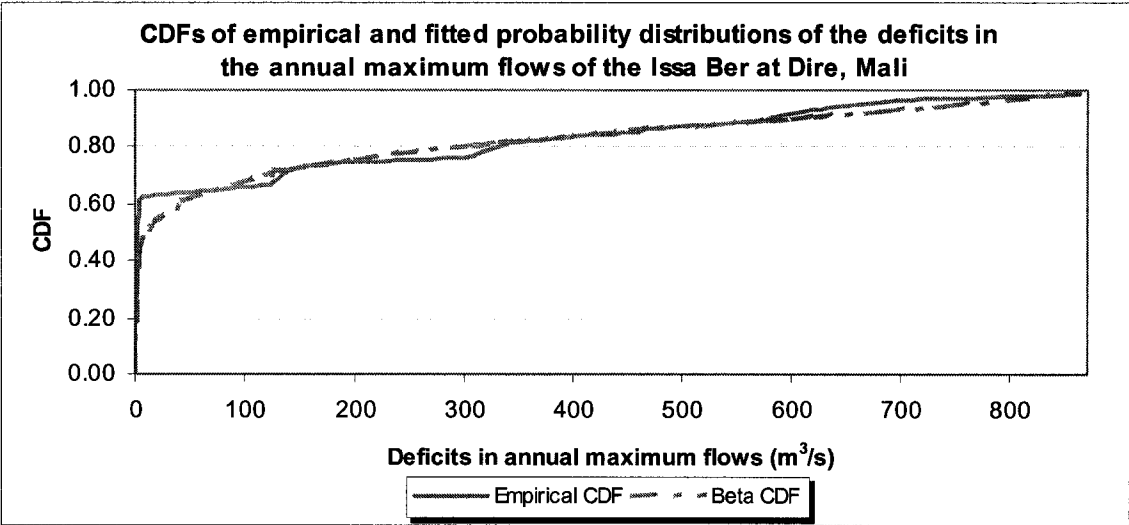
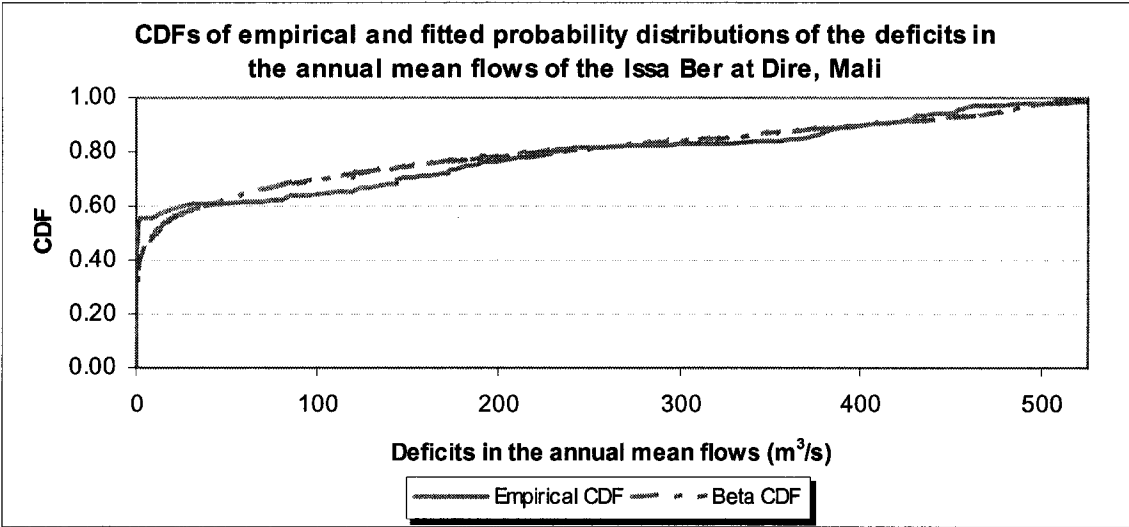
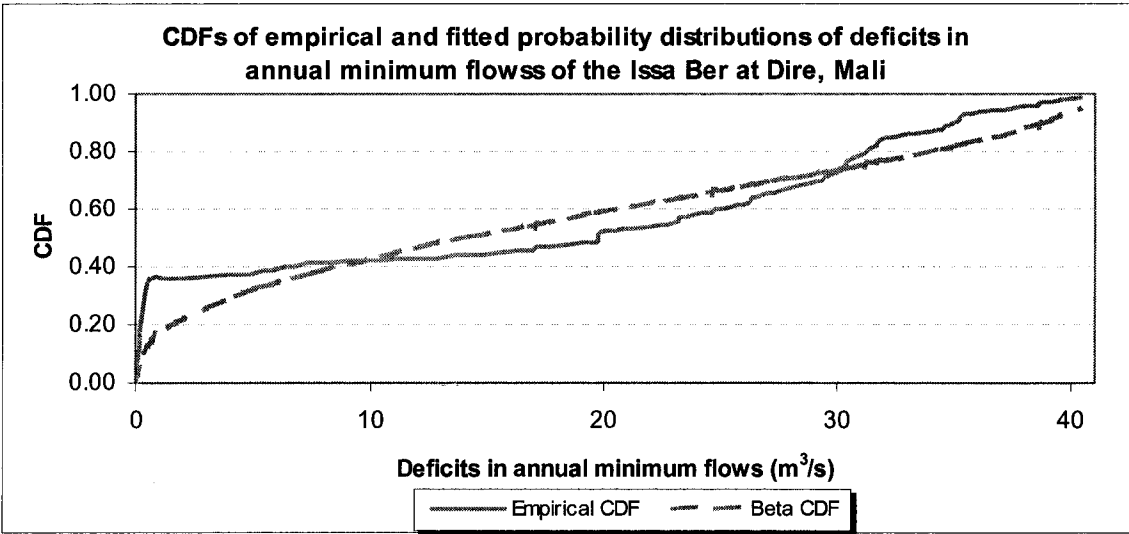


Figure 3.3.4.2-4: Probability distributions of deficits in flows of the Issa Ber at Dire, Mali

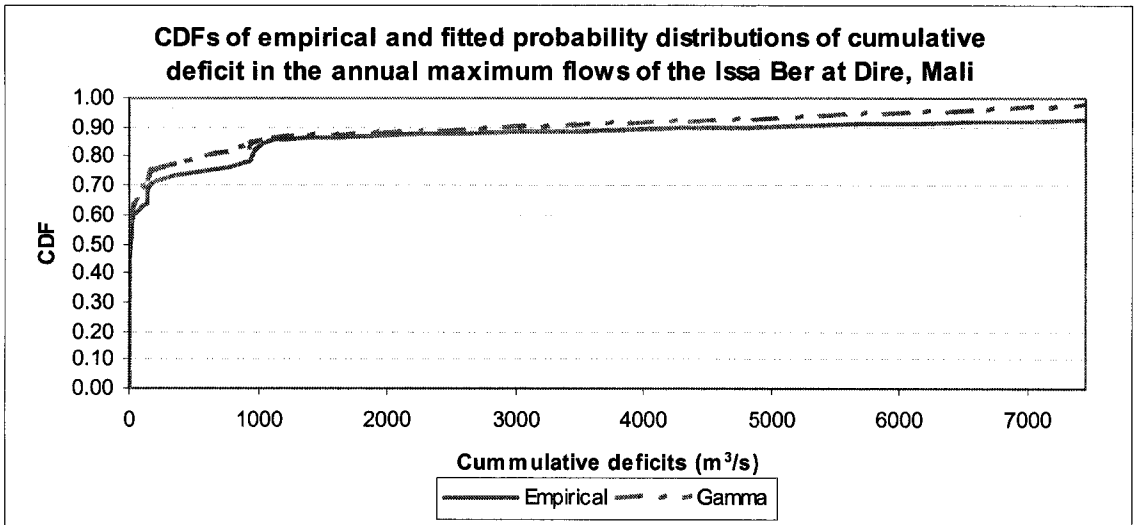
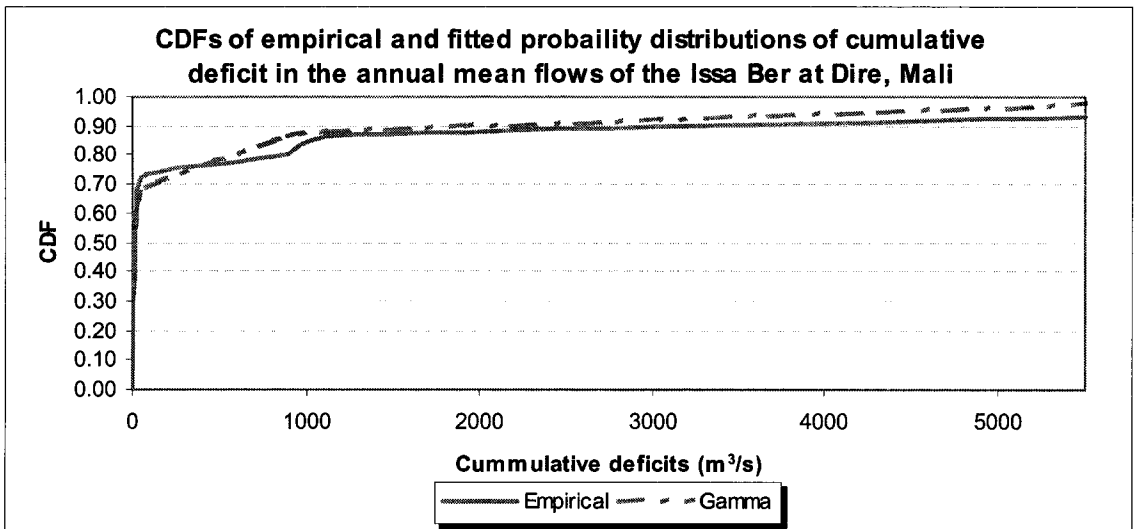
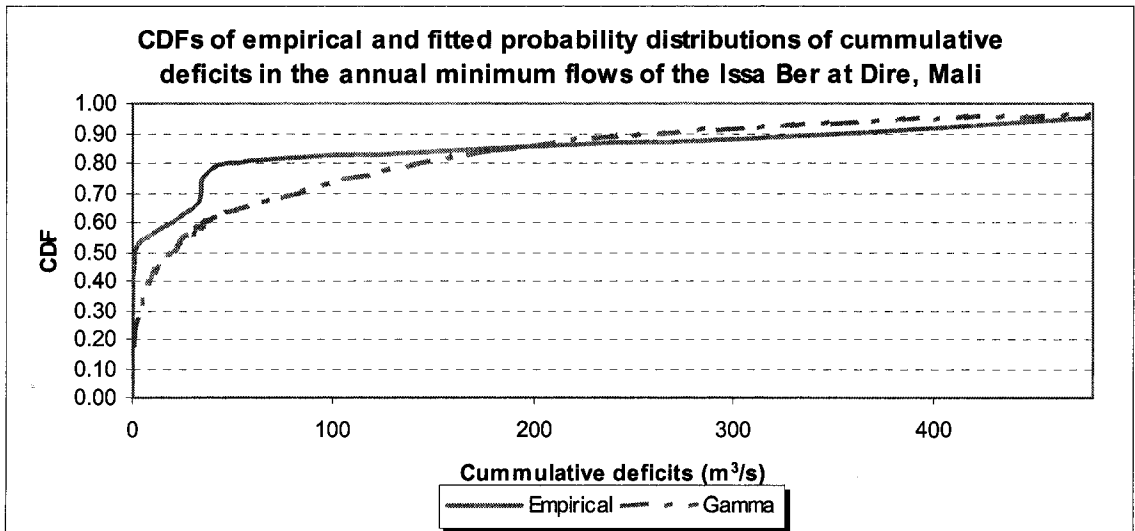


Figure 3.3.4.2-5: Probability distributions of the cumulative deficits in the flows of the Issa Ber at Dire, Mali

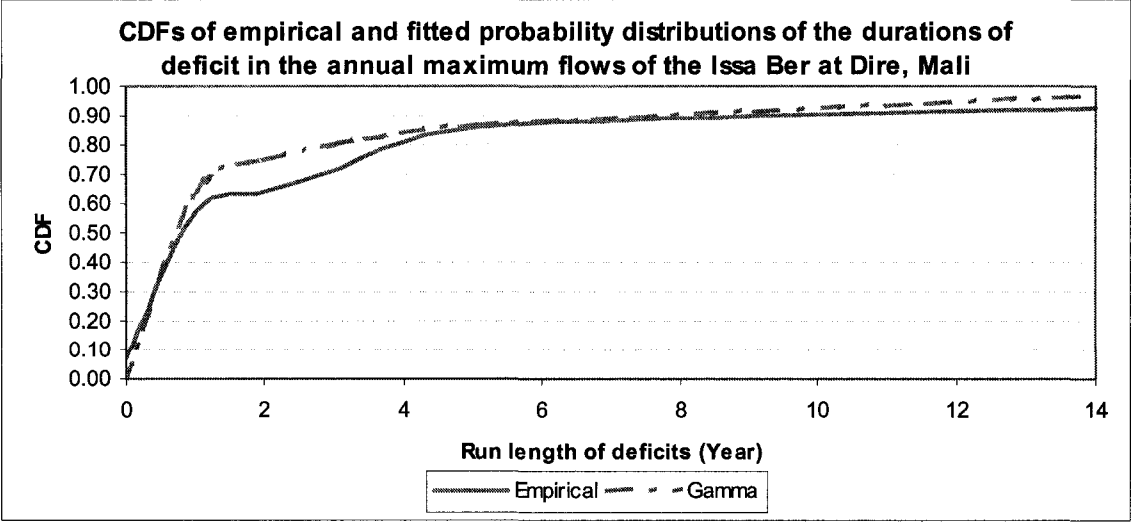
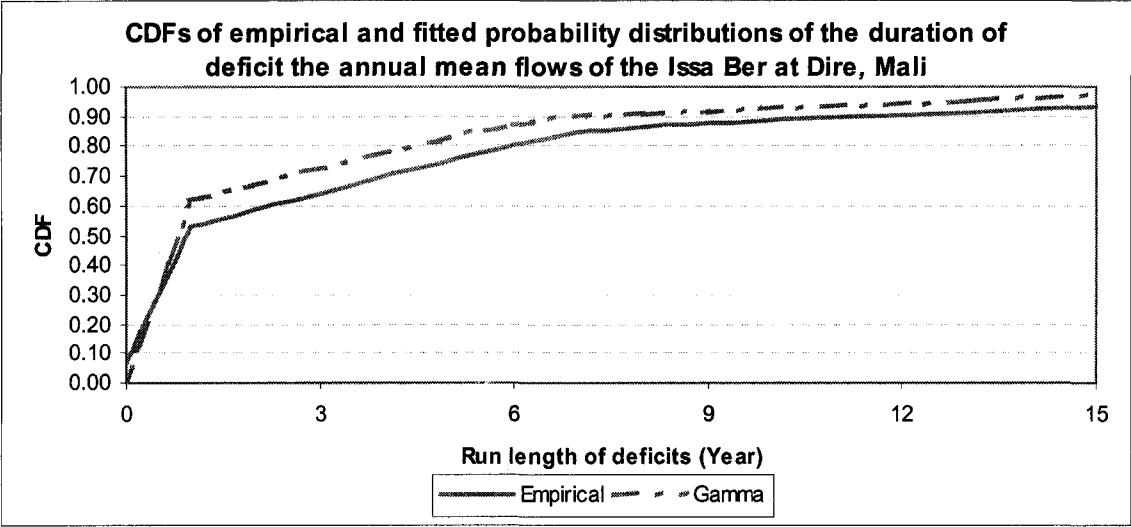
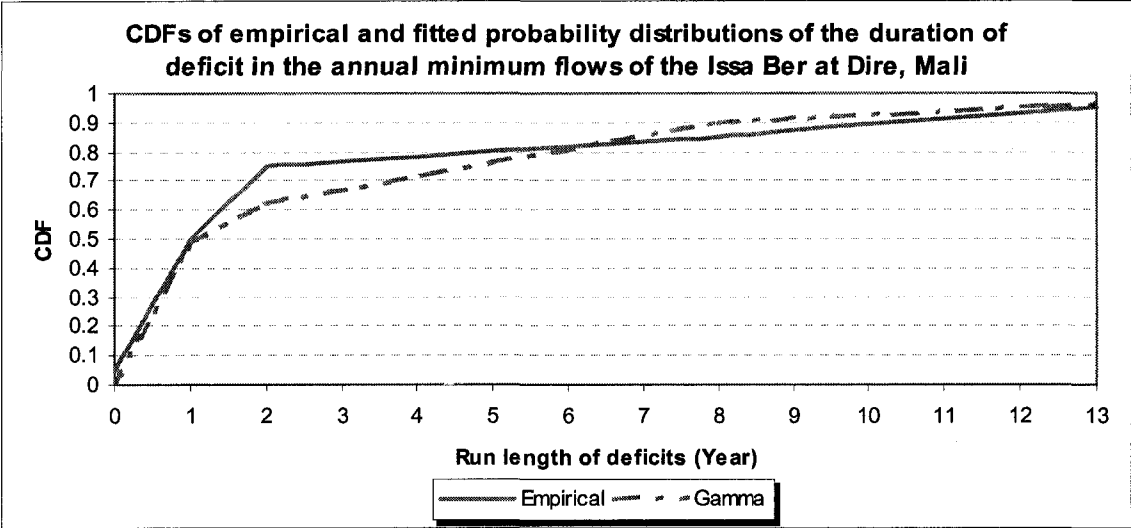


Figure 3.3.4.2-6: Probability distributions of the durations of deficits in the flows of the Issa Ber at Dire, Mali.

### 3.3.4.3. Flow sustainability

At this gaging station too, the sustainability indices of the annual minimum flows, compared to those of other flow types have a steeper slope, meaning a pronounced sensitivity to deficit. The sustainability indices of the annual mean and maximum flows have linear trends with about the same slope; they have similar sensitivities to deficits.

Drought Impacts on Discharges	Performance Indicator	Annual Minimum Discharges	Annual Mean Discharges	Annual Maximum Discharges
<b>Single Year Deficits</b>	Reliability	$24/71 = 0.34$	$38/71 = 0.54$	$43/71 = 0.61$
	Resilience	$24/71 = 0.34$	$35/71 = 0.49$	$33/71 = 0.46$
	Conditional Expected Vulnerability	$1180.82/49 = 24.09$	$7640.04.19/34 = 224.71$	$9838.87/38 = 258.92$
	Relative Vulnerability (Expected)	$24.09/862.82=0.03$	$224.71/862.82=0.26$	$258.92/862.82=0.30$
	Sustainability	0.111	0.195	0.197
<b>Cumulative Deficits</b>	Reliability	$9/19 = 0.47$	$7/14 = 0.50$	$7/13 = 0.54$
	Resilience	$9/19 = 0.47$	$6/14 = 0.43$	$6/13 = 0.46$
	Conditional Expected Vulnerability	$1180.424/10= 118.04$	$7640.03/7 = 1091.43$	$9838.87/6 = 1639.81$
	Relative Vulnerability (Expected)	$118.04/7439.44 = 0.02$	$1091.43/7439.44 = 0.15$	$1639.81/7439.44 = 0.22$
	Sustainability	0.22	0.18	0.19
<b>Deficits Duration</b>	Reliability	$9/19 = 0.47$	$7/14 = 0.50$	$7/13 = 0.54$
	Resilience	$9/19 = 0.47$	$6/14 = 0.43$	$6/13 = 0.47$
	Conditional Expected Vulnerability	$38/10 = 3.8$	$33/7 = 4.71$	$28/6 = 4.75$
	Relative Vulnerability (Expected)	$3.8/15 = 0.25$	$4.71/15 = 0.31$	$4.75/15 = 0.32$
	Sustainability	0.17	0.15	0.17
<b>Relative Sustainability</b>		<b>0.499</b>	<b>0.525</b>	<b>0.561</b>

Table 3.3.4.3-1: Flow Sustainability Indices for the expected values of flow deficits and duration of deficit in the flows of the Issa Ber at Dire, Mali

Drought Impacts on Discharges	Ranking for Sustainability		
	Annual Minimum Discharges	Annual Mean Discharges	Annual Maximum Discharges
Single Year Deficits	1	2	3
Cumulative Deficits	3	1	2
Duration of Deficits	2	1	3
Overall	1	2	3

Table 3.3.4.3-2: Ranking of the flow types by flow sustainability indices

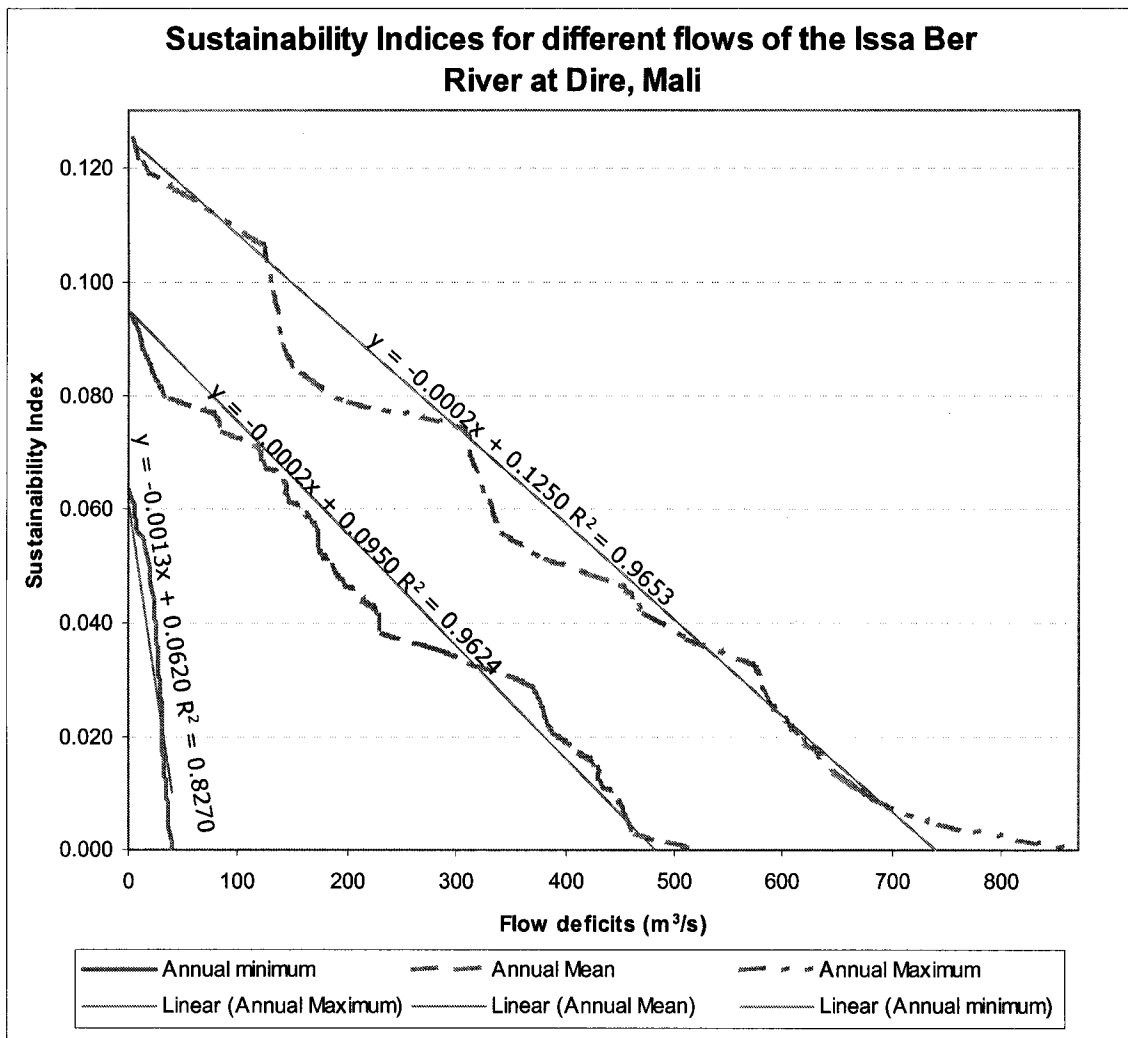


Figure 3.3.4.3-1: Sustainability Indices of different flow types of the Issa Ber at Dire, Mali

Deficit in Annual Discharge (m <sup>3</sup> /s)			Vulnerability (Exceedence Probability)			Reliability			Resilience			Sustainability Index		
Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
0.52			0.979			0.34	0.54	0.61	0.19	0.18	0.21	0.063		
1.42			0.957									0.062		
4.62			0.93									0.061		
5.52			0.91									0.059		
6.72			0.89									0.058		
7.62			0.87									0.056		
12.2			0.85									0.055		
14.2			0.83									0.054		
16.8			0.80									0.052		
17.2			0.78									0.051		
19.6			0.76									0.050		
19.7			0.74									0.048		
19.8			0.72									0.047		
21.2			0.70									0.045		
22.7	1.27		0.68	0.970								0.044	0.094	
23.2	8.88		0.66	0.939								0.043	0.091	
23.3	12.50		0.63	0.909								0.041	0.088	
24.4	19.13		0.61	0.879								0.040	0.086	
24.9	25.20		0.59	0.848								0.039	0.083	
26.0	38.20	2.82	0.57	0.818	0.96							0.037	0.080	0.125
26.3	77.84	12.82	0.55	0.788	0.92							0.036	0.077	0.121
26.4	86.96	42.82	0.53	0.758	0.89							0.034	0.074	0.116
27.3	116.88	42.82	0.51	0.727	0.89							0.033	0.071	0.116
27.8	123.35	122.82	0.48	0.697	0.82							0.032	0.068	0.107
28.5	143.16	122.82	0.46	0.667	0.82							0.030	0.065	0.107
29.3	143.54	132.82	0.44	0.636	0.75							0.029	0.062	0.097
29.5	162.44	132.82	0.42	0.606	0.75							0.028	0.059	0.097
29.9	172.40	142.82	0.40	0.576	0.67							0.026	0.056	0.088
30.3	173.68	162.82	0.38	0.545	0.64							0.025	0.053	0.083
30.3	185.13	202.82	0.38	0.515	0.60							0.025	0.050	0.079
30.4	194.08	302.82	0.34	0.485	0.57							0.022	0.047	0.074
30.8	215.59	312.82	0.31	0.455	0.53							0.021	0.044	0.070
31.2	228.82	312.82	0.29	0.424	0.53							0.019	0.041	0.070
31.4	231.94	332.82	0.27	0.394	0.46							0.018	0.038	0.060
31.7	283.86	342.82	0.25	0.364	0.42							0.017	0.035	0.056
31.8	315.44	382.82	0.23	0.333	0.39							0.015	0.032	0.051
32.1	365.34	452.82	0.21	0.303	0.35							0.014	0.029	0.046
33.4	375.61	472.82	0.19	0.273	0.32							0.012	0.027	0.042
34.5	381.03	512.82	0.17	0.242	0.28							0.011	0.024	0.037
34.6	389.01	572.82	0.14	0.212	0.25							0.010	0.021	0.032
35.2	414.15	582.82	0.12	0.182	0.21	0.008	0.018	0.028						
35.2	428.99	602.82	0.10	0.152	0.17	0.007	0.015	0.023						
35.5	430.67	622.82	0.08	0.121	0.14	0.006	0.012	0.019						
36.7	450.00	622.82	0.06	0.091	0.14	0.004	0.009	0.019						
38.3	454.16	682.82	0.04	0.061	0.07	0.003	0.006	0.009						
38.8	466.44	742.82	0.02	0.030	0.03	0.001	0.003	0.005						
40.3	524.37	862.82	0.00	0.000	0.00	0.000	0.000	0.000						

Table 3.3.4.3-3: Flow sustainability indices of flows of the Issa Ber at Dire, Mali

### **3.3.5. Discussion of the results of the assessments**

When selecting the four gaging stations, the objectives of the study were to have each of them provide information on drought impacts in specific reaches of the Niger and Bani Rivers in their courses in Mali, and assess the sustainability of the flows:

- ✓ The gaging station at Koulikoro is expected to provide information relevant to the entire upper basin of the Niger River. At this station, there seems to be strong linear autocorrelation between annual flows of the same type. For the annual minimum, mean and maximum flows, the correlation is extending to 6, 10 and 11 years respectively. At the meantime however, the different types of flows seem not to be correlated to each other;
- ✓ The gaging station at Douna controls nearly all the water the Bani River is discharging into the Niger River. The three flow types seem not have significant autocorrelation or cross-correlation;
- ✓ The gaging station on the Niger River at Mopti controls only part of the waters discharged into the Inner Delta. Here the autocorrelation are strong and quasi-linear; it extends to about 6 years for the annual minimum flows, and to 20 years for both the annual mean and annual maximum flows. This underscores the importance of the impact of the Inner Delta on the flow regime of the Niger River;
- ✓ The gaging station at Dire may provide information on part the flows of the Niger River flows at the exit from the Inner Delta where a

substantial part of water is lost. Not only are flows strongly autocorrelated among themselves, they are also correlated to the other types of flows.

Based on the long-term average values of the three types of flows, there is a similar pattern of occurrence of flow excesses and deficits at the four gaging stations on the Niger River and its tributary of the Bani River. Three main periods of deficits from 1907 to 1928, from 1936 to 1950 and from 1971 to 1994 may be identified in all the flow types. The years or periods of deficits in the flows have been alternating with years and sequences of years with excesses. The last episode of flow deficits that started in the early 1970 has been particularly long and severe may be still going on.

There are similarities and contrasts in drought impacts on the three types of flow at the four gaging stations. These similarities and contrasts may be found in the single-year flow deficits, their cumulative deficits, run lengths or the sustainability of flows.

#### **3.3.5.1. Flow deficits**

At each of the four stations under consideration, the three flow types have sustained more or less severe deficits the same year or consecutive years. For all the flow types and at all gaging stations, deficits have occurred more frequently and with increased severity over the last three decades.

For each gaging station, the intensity of the deficits or the ratio of the deficits is most severe in the annual minimum flows; the intensity of deficits in the annual minimum flows varies from 0 (for years with excess) to 100%.

The comparison of the assessment results at the four gaging stations shows:

- ✓ An increasing trend in the severity of the deficits in annual minimum flows from south to north, which calls for giving priority to the management objectives relying on low flows;
- ✓ A sharp difference between the regime of the Bani River upstream of Douna and the Niger River proper, as evidenced by the contrast between the trend of deficits in their flows at Koulikoro and Douna. Unlike the Niger River, which has had years of flow excess after the start of the deficit sequence of the 1970s, the Bani River does not show a significant sign of recovery.
- ✓ The difference in the intensity of deficit between the flow types of the same station suggests that other factors than rainfall deficits may be involved.

Gaging station	Discharge Type	Deficit intensity (%)	
		Average	Maximum
Koulikoro	Annual minimum	51	72
	Annual mean	43	55
	Annual maximum	40	63
Douna	Annual minimum	79	100
	Annual mean	50	83
	Annual maximum	47	83
Mopti	Annual minimum	64	95
	Annual mean	36	59
	Annual maximum	32	53
Dire	Annual minimum	82	94
	Annual mean	38	54
	Annual maximum	26	42

Table 3.3.5.1-1: Summary of the intensity of deficits in the flows at different gaging stations

Changes in land use in the basin have the potential to affect the runoff coefficient and the recharge of adjacent aquifers, and subsequently impact the baseflow. In the case of the Bani River, there is urgency to investigate the causes of the consistent decreasing trend observed in all the three flow types. In this regard, one of the areas to look into may be the potential increase in sediment transport and deposit resulting from agricultural development in the basin.

Whatever the cause of the increased severity of the deficits in the annual minimum flows, and in absence of flow regulation, the objectives of water resources management relying on baseflow are at a greater risk of sustaining deficits; this risk is increasing from south to north.

At all gaging stations, of the deficits in the three flow types, those in the annual minimum discharges exhibit the smallest coefficient of variation, followed by the deficits in the annual mean discharges.

### **3.3.5.2. Flow sustainability**

The results of sustainability assessment show again that at the same level of deficits, the annual minimum flows are less sustainable than other types of flow of the Niger and the Bani Rivers. In the particular case of the Bani River, any levels of deficits may cause the flows to be unsustainable.

At all the gaging stations, the rate of change in the sustainability index with respect to the deficits in the annual minimum flows is faster than it is in other flow types.

Like the different types of flow they rely on, the management objectives are sensitive to deficits. The sustainability indices corresponding to the potential flow deficits may be used in the determination of the priority order of the management objectives in an MCDA model. Due to other constraints, the definition of the priority order may include factors other than the sustainability indices.

## **4. THE MODEL OF MULTICRITERIA DECISION ANALYSIS (MCDA)**

### **4.1. MODEL DEVELOPMENT**

#### **4.1.1. Approach**

As the review of literature has revealed, for most states in the USA, and many other countries, contingency planning has become a standard practice in drought preparedness. However, even with drought plans drawn from existing planning frameworks, there is potential for problems to arise in drought impacts management. In particular, the mitigation strategy needs to be consistent with the management objectives at all severity stages of drought, and with the conditions before and after the occurrence of drought. Therefore, the implementation of a drought plan may have to address such critical issues as:

- ✓ The identification and selection of the management options most relevant to the different phases of a developing drought in presence of conflicting management objectives and different players;
- ✓ The timing and sequencing of the implementation of the selected management actions in order to achieve the most effective mitigation and consistency of drought impacts management with pre- and post-drought conditions. Due to the chronic lack of local resources in poor countries and the length of time necessary to mobilize external resources, these problems may be of greater importance.

The search for solution to the problems identified above comes down to defining an implementation strategy, which is consistent in terms of strategic, tactical and emergency management of drought impacts. To achieve this goal, the management strategy has to be flexible enough to adapt to a developing drought. Therefore, it needs to have both the strategic, tactical, and emergency components. Ultimately, the management strategy must be dynamic in order to respond to changes in drought severity and be consistent with the strategic objectives before and after the drought.

Over the recent years, different methods have been proposed for assessing the potential of water projects to achieve sustainability. This research applied two of the proposed methods to drought impacts management for managing the immediate and long-term effects and achieving sustainability (ASCE, 1998):

- ✓ The first method is the *Weighted Statistical Indices*, which was applied to a river system for assessing its sustainability under the existing conditions;
- ✓ The second method, the *Weighted Criteria Indices* was applied to the selection of the alternative actions most relevant to drought impacts management.

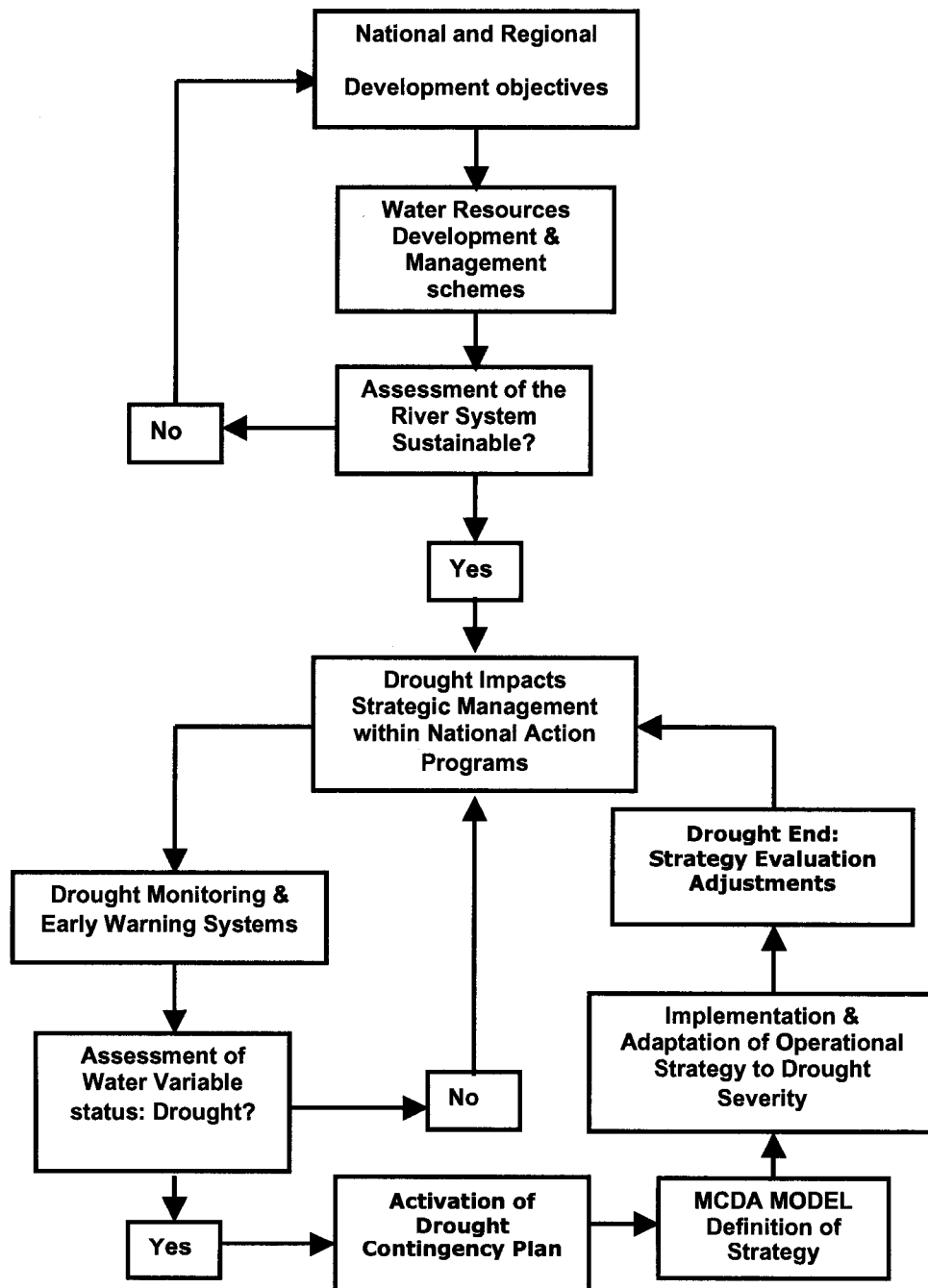
#### **4.1.2. Methodology**

For water resources development in the USA, "The Principles and Guidelines" may be applied to the selection of the best alternative plan. They may also

be used for the identification of the best alternative contingency plan for drought impacts management (the US Army Corps of Engineers, 1994.) However, drought impacts mitigation is a dynamic management problem, which may involve conflicting management objectives, alternative actions and different players. As such, the management problem may be formulated as one of minimizing the levels of deficits in the management objectives rather than maximizing utility (Zeleny, 1982). The sustainability of the management objectives of water projects with respect to the deficits may be a performance indicator as suggested by different methods, including the *Weighted Criteria Indices* and the *Weighted Statistical Indices* developed by the Delft Hydraulic Laboratory, Netherlands (ASCE, 1998.) In chapter 3, section 3.2, the latter method was applied to the Niger River system in order to assess the sustainability of its different flows under drought conditions.

For drought impacts management, instead of water projects, the method of *Weighted Criteria Indices* is modified and applied to individual management options with potential for mitigation of drought impacts. The assessment consists of determining the extent to which the implementation of an alternative action may be relevant and sustainable; the assessment results in the determination of the *Relevance and Sustainability Index (RSI)* of the assessed potential mitigation option. The relevance and sustainability indices may be used to compare and rank the different management options. For an alternative option, the rank may reflect the opportunity of its implementation at any management phase of drought impacts.

Figure 4.1.2-1: Flow chart of the strategy for the sustainable management of drought impacts



As its name implies, the method of the *Weighted Criteria Indices* is an assessment procedure involving multiple criteria and sub-criteria, which makes it a good candidate for the application of Multicriteria Decision Analysis (MCDA) technique.

To fit the conditions for applying the MCDA technique, the search for solutions to the problem of drought impacts management is formulated as the following three-step procedure. The first step consists of identifying all the management goals and objectives, and the alternative actions with potential for mitigation. The second step consists of defining the performance criteria and sub-criteria and their weight; the weight may reflect the management phase or express the preference of decisions-makers. The third step applies the MCDA technique for assessing the Relevance and Sustainability, and for ranking the different alternative actions. When drought occurs, water uses may be affected to different extents.

Using the assessment results of the potential management options for the different management stages, a course of action may be defined such that it meets both the overall management objective and the need for consistency with the conditions before and after drought. The course of action may well be a combination of management actions of strategic, tactical, and emergency nature. If this were the case, drought impacts management would have achieved an important goal, which is the integration of the strategic, tactical, and emergency management objectives. In poor countries,

integrating the strategic, tactical, and emergency objectives of drought impacts management has been identified as critical to the consistency in development policies.

To apply the procedure, a spreadsheet model is designed to help decision makers identify the best management measures possible for drought impacts management. The selected management actions may provide the basis for designing drought impacts management strategies that best fit the management needs at all the development phases of drought: before, during and after the occurrence of drought.

#### **4.1.3. THE MODEL**

The objectives of drought impacts management are defined with regard to the management objectives for the impacts sustained or anticipated in any given case of drought (The US Army Corps of Engineers, 1994); they may be of strategic, tactical, and emergency nature.

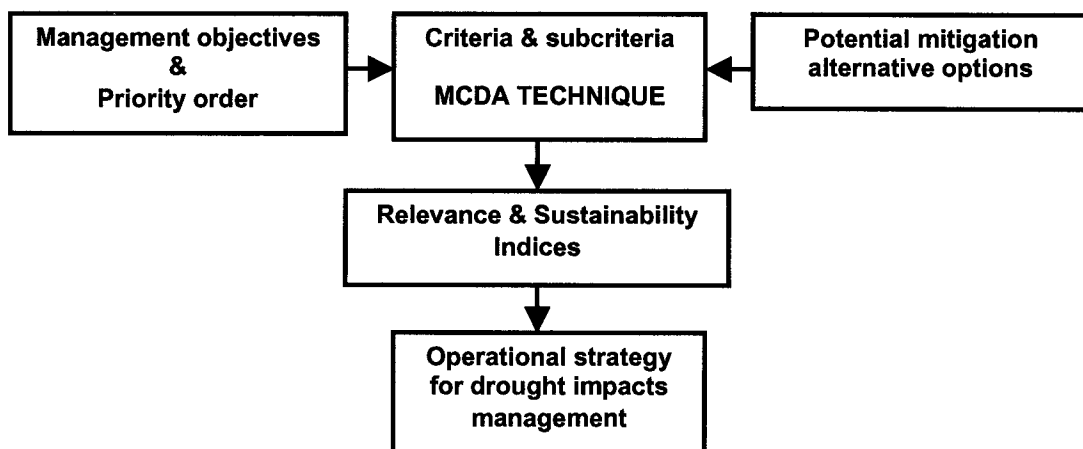


Figure 4.1.3-1: The Model of drought impacts management

The management objectives may be defined as illustrated in the following table:

**Table 4.1.3-1: Definition of Drought Preparedness Planning objectives**  
(Adapted from the US Army Corps of Engineers, 1994)

<b><u>Drought caused management</u></b>	<b><u>Management Objectives</u></b>
<b><u>Problems</u></b>	
<ol style="list-style-type: none"> <li>1. Rainfall deficit may cause flows of the river and its tributaries to fall below the required levels during the period of low flows of the dry season.</li> <li>2. During periods of low flows, the raw sewage from urban areas and mine tailings may not be assimilated adequately</li> <li>3. Due to the deficit in aquifer recharge, the depth of groundwater table is such that it becomes difficult for dug wells to tap it.</li> <li>4. Deficits in inflows may result in the drastic reduction of time for navigation</li> <li>5. Insufficient volumes of flood water in plains and irrigated lands may adversely affect agriculture and fishing</li> <li>6. If insufficient inflows prevent the reservoir to store water at full capacity, the stored volume needs to be managed optimally</li> </ol>	<ol style="list-style-type: none"> <li>1. Regulate the river and tributaries in order to maintain the minimum flow, which allows the intake of different water uses</li> <li>2. Maintain water quality standard downstream of urban areas and mining point-sources discharges</li> <li>3. Provide rural areas and shantytowns with alternative water supplies during periods of drought</li> <li>4. Build reservoirs capable for regulating the flows</li> <li>5. Increase the reliability of fish and cereal production, which rely on flood waters</li> <li>6. Improve reservoir management by contingency planning</li> </ol>

Like the objectives, the response actions may be of strategic, tactical, and emergency nature. The following is an example list of potential options.

Responses	Response type		
	Emergency	Tactical	Strategic
<b><i>Supply augmentation</i></b>			
New storage			✓
Reallocation of supplies	✓	✓	✓
New system interconnections			✓
Water reuse		✓	✓
Groundwater mining	✓	✓	✓
High flow skimming	✓	✓	
Interbasin transfer	✓	✓	✓
Diversion	✓	✓	✓
System improvement		✓	✓
Conjunctive use	✓	✓	✓
Institutional change			✓
Technological innovation			✓
Conditional reservoir operation	✓	✓	
Operational coordination between system	✓	✓	✓
<b><i>Demand modification</i></b>			
Legal measures			✓
Pricing changes		✓	✓
Public awareness/education		✓	✓
Conservation credits	✓	✓	✓
Prioritizing demands	✓	✓	✓
Water conservation techniques		✓	✓
Alternatives to water-dependent activities	✓	✓	✓
<b><i>Impacts minimization</i></b>			
Forecasting/monitoring systems			✓
Regulation of consumption			✓
User discretion	✓	✓	
Interstate emergency action	✓	✓	
Conflict management		✓	✓
Insurance			✓
Spread of risk			✓
Compensation of damage	✓	✓	✓
Disaster relief	✓		
Reserve funds		✓	✓
Modify events	✓	✓	
Damage recovery	✓	✓	✓
Change in water uses		✓	✓
<b><i>Environmental and water quality change</i></b>			
Reduction in required low flows	✓	✓	
Alternative means of achieving water quality		✓	✓

Table 4.1.3-2: Potential management responses to drought in the USA

(Adapted from US Army Corps of Engineers, 1994; Neil Grigg, 1988)

As shown in the list above, potential management actions may be tangible or intangible; they may also be used for supply augmentation, demand modification, or impacts minimization. As such, the management options are of different nature and

The MCDA model is developed in Excel spreadsheet, and uses the technique of compromise programming (Zeleny, 1982), which is an interactive method. The model is flexible enough to be able to accommodate all the levels of drought severity and decision-makers' preferences for the different management objectives.

For an alternative, the overall performance for all criteria and sub-criteria is assessed by the following compromise programming formula:

$$\text{Minimize } Lp = \sum_{i=1}^j w_{ci} \left[ \frac{F_{iN}^* - F_{in}}{F_{iN}^* - F_{iN}^{**}} \right]^p \quad (\text{Equation 4.3-1})$$

Where:

- ✓  $w_{ci}$  is the product of weights assigned to criterion  $c$  and sub-criterion  $i$ ;
- ✓  $p$  is the power applied to compromise programming; in this paper the performance of alternatives will be assessed and ranked for  $p = 1, 2$  &  $10$ .
- ✓  $F_{iN}^*$  is the best of all  $N$  alternatives' performance values for sub-criterion  $i$ ;

- ✓  $F_{IN}^{**}$  is the worst of all  $N$  alternatives' performance values for sub-criterion  $i$ ;
- ✓  $F_{in}$  is the actual value of alternative  $n$  for sub-criterion  $i$ ;
- ✓  $i$  is the number of sub-criteria;
- ✓  $N$  is the total number of alternatives;
- ✓  $n$  is any of the  $N$  alternatives under consideration.

Figure 4.1.3-1 shows a worksheet of the Excel spreadsheet.

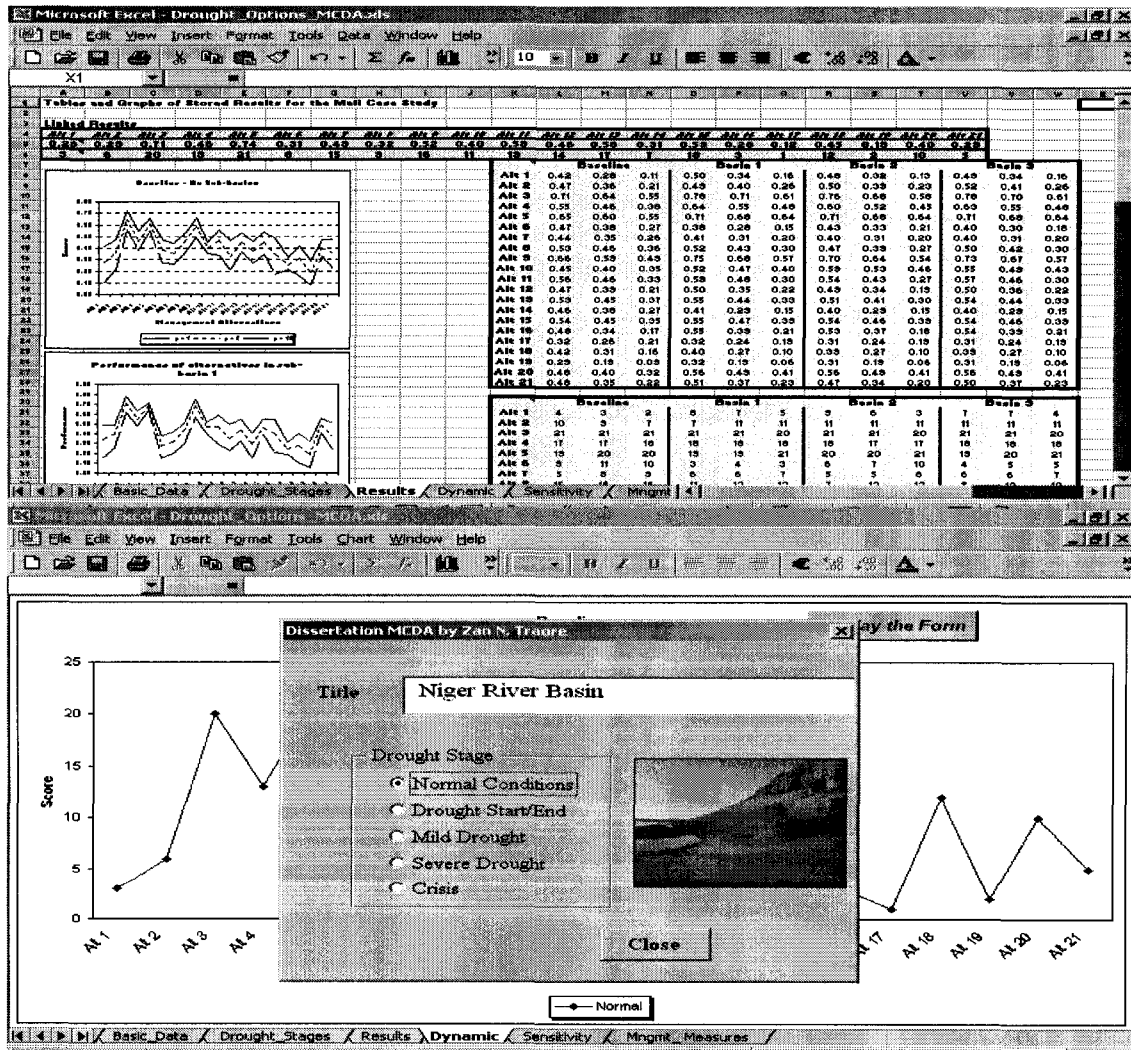


Figure 4.1.3-2: Example pages of the Excel spreadsheet of the Model

Compromise programming, except for standardizing the performance scores into the range of 0 to 1, is similar to other value-based MCDA methods. In particular, for  $p = 1$ , the performance scores of alternatives are very similar to those that the method of weighted average would produce, except that the lowest score is the more preferred. For  $p = 2$ , the difference in the ratings is accentuated, that is lesser emphasis is given to the lower ratings and greater emphasis is given to the higher ratings. For  $p = 10$  (or infinity at the limit), compromise programming produces a table with either zeros or ones. The ratings of one indicate the worst possible alternative for a specific criterion. The use of the different values of the power  $p$  provides a quick method to determine the sensitivity of the solution. In general, compromise programming uses  $p = 1, 2$ , and infinity; in this paper,  $p = 10$  is used as a surrogate to the situation with infinity.

The model, for assessing of the management options whose relevance to the management objectives may evolve over the course of a given drought event, uses the criteria and sub-criteria defined in the following sub-section, and shown in table 4.1.3.1-1. Specifically, the criteria are the feasibility, sustainability or lasting effect, the opportunity for development, the relevance to the strategic, tactical and emergency management, and the impacts on the management objectives.

### **4.1.3.1. The criteria and sub-criteria**

The model uses five main criteria, which are assigned equal or different weights, depending on the priority order; each criterion consists of a number of sub-criteria, which may be assigned the same or different weights:

#### **4.1.3.1.1. Feasibility**

This criterion assesses the likelihood of the successful implementation of the alternative option under the prevailing socio-economic conditions. It divides into the following sub-criteria:

- ✓ *Costs* may be, in the context of poverty, a major constraint to the implementation of an alternative action, especially, when it has to be dealt with on short notice, as is the case for drought; it is to be minimized. For the most common infrastructure used to provide water supply services in Mali, the unit costs are the following (DNH, 2000): (1) Dug well: \$ 300 (200,000 F CFA), (2) Water well: \$ 12,000 (7 406,875 F. CFA), (3) Big diameter water well: \$ 22,000 (13,401,000 F CFA), and Rural water distribution system: \$ 100,000 (60,000,000 F CFA). Based on these figures, the ranges for rating the costs are defined as follows:
  - No cost: "None";
  - Cost less than \$10,000 is "Low";
  - Cost between \$10,000 and \$50,000 is "Medium";
  - Cost between \$50,000 and \$100,000 is "high";

- Cost higher than \$100,000 is "Very high";
- ✓ The *availability of funding* or the access to financing at local level to cover the costs assesses the ability of the local community to fund the activities of drought impacts management. If no local funding were available, then drought impacts management has to turn to potential external sources, which may cause significant delay to the implementation; the sub-criterion is to be maximized and is rated as follow:
  - "None" when there is no funding;
  - "Poor" when up to 25% of the necessary funding is available;
  - "Fair" for availability of funding between 25% and 50%;
  - "Good" when the availability of local funding covers costs between 50% and 75%;
  - "Excellent" when the costs are covered locally for more than 75%.
- ✓ The *availability of local expertise*, like the availability of funding, may be another constraint to the implementation of an alternative action, if it requires external technical assistance, which may not be the best choice for tactical and emergency management; the sub-criterion is to be maximized
  - "None" when none of the necessary expertise exists;
  - "Poor" when up to 25% of the necessary expertise is available;
  - "Fair" when the availability of local expertise is between 25% and 50%;

- "Good" when 50% to 75% of the expertise is available locally;
  - "Excellent" when more than 75% of needed expertise is available at local level.
- ✓ *The time to raise the funds necessary to cover the costs, if not available locally, is a sub-criterion to be minimized; it is rated as:*
- "None" when there is no time involved;
  - "Short" for time period shorter than three months;
  - "Average" for cases taking three to six months to raise funds;
  - "Long" corresponds to fund-raising time period between six and nine months;
  - "Very Long" for alternatives requiring more than nine months to raise funds.
- ✓ *The mobilization and implementation time is to be minimized, and is rated as:*
- "None" when there is no time involved;
  - "Short" for time period shorter than three months;
  - "Average" for cases taking three to six months for mobilization and implementation;
  - "Long" corresponds to mobilization and implementation time between six and nine months;
  - "Very long" for alternatives requiring more than nine months for mobilization and implementation.

#### **4.1.3.1.2. Sustainability**

The sustainability criterion is intended to assess the long-term effect of the alternative, or its ability of self-sustaining; it divides into:

- ✓ *Prospect for costs (Capital and rehabilitation costs, and operating and maintenance costs) recovery* sub-criterion determines to what extent the alternative option has a potential to generate locally the funds necessary for the operation, maintenance and renewal of the system without external intervention. Without self-generated funds, the management action is not likely to last long; it is to be maximized and is rated as:
  - "None" when there is no prospect for the recovery of any portion of the costs;
  - "Poor" when there are chances to recover at most 25% of the costs;
  - "Fair" when 25% to 50% of costs can be recovered;
  - "Good" when there are chances to recover 50% to 75% of the costs;
  - "Excellent" for an alternative with potential of more than 75% of costs recovery.
  
- ✓ The *non-structural adaptability* sub-criterion refers to the potential for the management action to make any non-physical adjustment; it is to be maximized and is rated as:
  - "None" when the alternative has no ability to adapt;
  - "Poor" when the adaptability is at most 25%;

- "Fair" when the adaptability is between 25% and 50%;
  - "Good" when the adaptability of the alternative ranges from 50% to 75%;
  - "Excellent" when the adaptability is beyond 75%.
- ✓ The *reliability* sub-criterion is the probability for an alternative to be within the satisfactory range; it is maximized and is rated as:
- "None" when the option has no reliability;
  - "Low" when the reliability is at most 25%;
  - "Medium" when the reliability is between 25% and 50%;
  - "High" when the reliability is between 50% to 75%;
  - "Excellent" for reliability higher than 75%;
- ✓ The *availability of local expertise for the operation and maintenance* sub-criterion is very similar to the *availability of local expertise* sub-criterion of the feasibility criterion, therefore it is rated the same way;
- "None" when no expertise exists locally;
  - "Poor" when up to 25% of the expertise is available locally;
  - "Fair" for availability between 25% and 50%;
  - "Good" when 50% to 75% of the expertise is available;
  - "Excellent" when all needed expertise is available locally;
- ✓ The *structural adaptability* refers to the ability of the management action to go through any physical adjustment; it is to be maximized and is rated more or less the same way the non-structural adaptability is.
- "None" when the alternative has no ability to adapt;

- "Poor" when the adaptability is at most 25%;
- "Fair" when the adaptability is between 25% and 50%;
- "Good" when the adaptability of the alternative ranges from 50% to 75%;
- "Excellent" when the adaptability is higher than 75%.

#### **4.1.3.1.3. Development opportunity**

The criterion of development opportunity is intended to evaluate the extent to which an alternative option contributes to local development; it divides into:

- ✓ *The opportunity for phased development* sub-criterion, which assesses the alternative for its potential to be integrated into a broader development objective to be implemented in multiple phases;
- ✓ *Local impacts* sub-criterion refers to the impacts of the management action on local conditions;
- ✓ *Potential poverty reduction* may refer to the potential impacts of the option in terms of economic benefits; an example would be how the option may improve the access of poor people to water supply and sanitation services, especially during drought;
- ✓ *Political sensitivity* is a criterion designed to assess the impact of the implementation of the alternative on the political stability at local, national and basin level.
- ✓ *Basinwide impacts* criterion refers to the extent to which the alternative action may affect existing conditions on basin scale;

#### **4.1.3.1.4. The relevance of the management action to:**

- ✓ *The Strategic management* sub-criterion is meant to determine to what extent an alternative option is relevant to the objectives of long-term drought impacts management; it is to be maximized. The assessment consists of answering either "Yes" or "No" to the question of whether or not the alternative has a strategic nature;
- ✓ *The tactical management* sub-criterion is designed to assess the potential for a management action to be used for tactical management. The management options relevant to tactical management are most preferable during a drought event. For the management actions relevant to both the strategic and tactical management, their implementation may make easy the transition between the two management phases. The assessment consists of answering either "Yes" or "No" where the alternative option has potential for the tactical management; the result of the assessment is to be maximized;
- ✓ *The emergency management* sub-criterion is similar to the other two sub-criteria of the relevance criterion. It is intended to assess an alternative option for its potential to achieve the objectives of emergency management. Emergency measures are only necessary and implemented under extraordinary circumstances, which might be unexpected drought severity or duration; this criterion is to be minimized;

#### **4.1.3.1.5. The potential impact of the management option on the management objectives**

This criterion is designed to assess the impacts of the alternative options on the management objectives; the sub-criteria of this criterion consist of the very management objectives of drought impacts management:

- ✓ *Water quality* sub-criterion is meant to assess the potential impact of the management option on water quality. When the flows are adversely affected by deficits during drought, raw sewage discharges into rivers may not be assimilated adequately. As result, there may be serious water quality problems;
- ✓ *Rural water supply*: Given the already insufficient provision of water supply and sanitation services in rural areas, drought may make this situation even worse. Therefore, it is important to assess an alternative option for its potential mitigation impact on rural water supply;
- ✓ *Urban water supply and sanitation*: drought can cause three main types of constraints to urban water supply. In particular: (1) the flow volume may be too low to allow sufficient water intake; (2) shanty towns in peri-urban areas, which are not serviced by piped water distribution system may experience increased problems to access water supply services; (3) sanitary conditions in urban areas may deteriorate as a result of drought;

- ✓ *Agriculture and fishing* may be very sensitive to drought conditions, especially in absence of infrastructure to regulate river flows;
- ✓ *Hydro-power generation* at plants on reservoirs with no annual carryover storage capacity will be affected by drought;
- ✓ *Navigation* is very dependant on the river flow volume, which can be critically reduced by drought.

This list of the management objectives is generic and may be adapted to the case under consideration; other criteria may be used too.

The assessment of the management options with respect to the different criteria may result in objective or qualitative values as shown in the table 4.1.3.1.5-1 (ASCE, 1998). For the qualitative values, an appropriate scale may be devised between the best and worse values in order to convert these values into quantitative terms. A multicriteria assessment method is then used to compare and rank the overall performance of the different alternatives. The results may be used for selecting the alternative or combination of alternatives that best achieve the objectives of drought mitigation. The assessment may exhibit sensitivity to the severity levels of drought events.

Criteria	Subcriteria	Optimiz.	Management alternatives Rating scale				
			1	2	3	4	5
Feasibility	Costs	Min	None	Low	Medium	High	Very high
	Availability of Funding	Max	None	Poor	Fair	Good	Excellent
	Availability of local expertise	Max	None	Poor	Fair	Good	Excellent
	Time to raise funds	Min	None	Short	Average	Long	Very Long
	Mobiliz. and Implement. time	Min	None	Short	Average	Long	Very Long
Sustainability	Prospect for costs Recovery	Max	None	Poor	Fair	Good	Excellent
	Non-Structural Adaptability	Max	None	Poor	Fair	Good	Excellent
	Reliability	Max	None	Low	Medium	High	Very high
	Availab. of expertise for O&M	Max	None	Poor	Fair	Good	Excellent
	Structural Adaptability	Max	None	Poor	Fair	Good	Excellent
Development Opportunity	Opport. for phased develop.	Max	None	Poor	Fair	Good	Excellent
	Local Impacts	Max	Very negat.	Negative	Indifferent	Positive	Very Positive
	Potential Poverty reduction	Max	None	Low	Medium	High	Very high
	Political sensitivity	Min	None	Low	Medium	High	Very high
	Basinwide Impacts	Max	Very negat.	Negative	Indifferent	Positive	Very positive
Relevance of The alternative Action to	The strategic Management	Max	No	Yes	-		
	The tactical Management	Max	No	Yes	-		
	Emergency Management	Min	No	Yes	-		
Impacts on the Management Objectives	Water Quality	Max	Very negat.	Negative	Indifferent	Positive	Very positive
	Rural water supply	Max	Very negat.	Negative	Indifferent	Positive	Very positive
	Urban water supply & sanitat.	Max	Very negat.	Negative	Indifferent	Positive	Very positive
	Agriculture and Fishing	Max	Very negat.	Negative	Indifferent	Positive	Very positive
	Energy generation	Max	Very negat.	Negative	Indifferent	Positive	Very positive
	Navigation	Max	Very negat.	Negative	Indifferent	Positive	Very positive

Table 4.1.3.1-1: Rating scale of management alternative measures for criteria and sub-criteria

#### 4.1.3.2. Model sensitivity

##### 4.1.3.2.1. Model sensitivity to drought severity

As seen in the review of literature, drought is unpredictable not only in its occurrence, but also in its duration and severity. Therefore, it is crucial to deal with these uncertainties and dynamic characteristics of drought as part

of a comprehensive modeling of drought impacts management. Stochastic programming may be a way of dealing with the uncertainties. However, given the fact that drought occurrence, duration and severity are independent variables, the uncertainties associated with each of them may have to be dealt with separately and concurrently. For stochastic programming, this complexity of the problem formulation may prove too difficult to handle.

As alternative to this complex formulation, this study proposes to simplify the problem by defining drought scenarios based on drought severity. As reviewed previously, drought intensity or severity, which may vary over time and space, has been expressed in terms of aggregate indices of different water or moisture variables (Hayes, 2002). The Standard Precipitation Index (SPI) is one of the aggregate indices used to assess drought status; the classification of drought intensity based on the values of the SPI is shown in table 4.1.3.2.1-1.

<b>SPI</b>	<b>Drought Intensity</b>
2.0+	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
-2.0 and less	Extremely dry

Table 4.1.3.2.1-1: Standardized Precipitation Index (SPI) values and corresponding drought Intensity (Adapted from Hayes, 2002)

Again, the data and expertise necessary for assessing the SPI and other similar indices may not always be available for immediate use, especially in developing countries. Therefore, this research used the degree of deficits in streamflows to assess drought status. As water or moisture availability evolves from normal situation to crisis, four development stages or scenarios may be identified as: Drought start/end, Mild drought, Severe drought, and Crisis. These stages or scenarios may correspond to the bottom four worse drought severity levels of the Standard Precipitation Index or to the ranges of flow deficits as defined in the table 4.2.1.2-1.

To adapt to the evolving drought, the strategy will consist of shifting from the strategic management toward the tactical, and eventually to the emergency ones. For the model, the shift is taken care of by allocating the weight to the strategic and emergency management sub-criteria in inverse proportion as shown in the table 4.2.1.2-2:

To keep the focus on the tactical management of drought impacts, it is assigned the highest weight in all drought scenarios. From the beginning of drought to the crisis stage, the strategic and emergency management objectives are assigned weights that vary in inverse order; in periods of excesses of no deficits, only the strategic objective is considered.

Intensity of Flow Deficits (% Long-term average value)	Drought Scenario	Weight of the management measures		
		Strategic	Tactical	Emergency
Excess or no deficit	Normal conditions	1	0	0
Less than 25%	Drought Start/End	4	5	1
Between 25% and 50%	Mild drought	3	5	2
Between 50% and 75%	Severe drought	2	5	3
More than 75%	Crisis	1	5	4

Table 4.1.3.1.2-2: Weight of management for different drought scenarios

#### **4.1.3.2.2. Model sensitivity to the weight assigned to the management objectives**

Depending on the location and drought intensity, some management objectives, compared to others, may be assigned higher priority. This priority order may be expressed by assigning weight to sub-criteria.

## **4.2. MODEL APPLICATIONS**

### **4.2.1. CASE STUDY: DROUGHT IMPACTS MANAGEMENT IN MALI**

#### **4.2.1.1. Assessment for different powers of compromise programming**

The model of drought management presented above is applied to a series of alternative options, which have been implemented in actual management of drought impacts in Mali and other African countries. The management actions to be assessed for the management decision-making are the following:

- ✓ Alternative 1: Drilling new water wells;
- ✓ Alternative 2: Water well rehabilitation;
- ✓ Alternative 3: Drilling big diameter wells;
- ✓ Alternative 4: Dug wells;
- ✓ Alternative 5: New municipal water distribution systems;
- ✓ Alternative 6: Municipal water system repair &/or extension;
- ✓ Alternative 7: New rural water distribution system (solar energy powered);
- ✓ Alternative 8: New rural water distribution system (diesel powered);
- ✓ Alternative 9: Rehabilitation of rural water distribution systems;
- ✓ Alternative 10: Water delivery by Mobile tankers;
- ✓ Alternative 11: Water delivery by individual vendors;
- ✓ Alternative 12: Village-level storage reservoir;
- ✓ Alternative 13: Application of a pricing rate structure;
- ✓ Alternative 14: Public education;

- ✓ Alternative 15: Conditional reservoir operation;
- ✓ Alternative 16: Prioritizing water uses;
- ✓ Alternative 17: Water resources monitoring/forecasting;
- ✓ Alternative 18: New large storages;
- ✓ Alternative 19: Regulatory measures;
- ✓ Alternative 20: Water uses restrictions;
- ✓ Alternative 21: Drought early detection and warning;

Criteria	Subcriteria	Optimization Type	Weight of sub-criteria			
			Base Line	Priority		
				Order 1	Order 2	Order 3
<b>Feasibility</b>	Cost	Minimize	1	3	3	3
	Availability of funding	Maximize	1	3	3	3
	Availability of expertise	Maximize	1	2	2	2
	Time to raise funds	Minimize	1	1	1	1
	Mobilization and implem. time	Minimize	1	1	1	1
<b>Sustainability</b>	Prospect for costs recovery	Maximize	1	3	3	3
	Non-structural adaptability	Maximize	1	1	1	1
	Reliability	Maximize	1	3	3	3
	Availab. of expertise for O&M	Maximize	1	2	2	2
	Structural adaptability	Maximize	1	1	1	1
<b>Development opportunity</b>	Opport. For phased develop.	Maximize	1	3	3	3
	Local impacts	Maximize	1	3	3	3
	Potential poverty reduction	Maximize	1	1	1	1
	Political sensitivity	Minimize	1	1	1	1
	Basin wide impacts	Maximize	1	2	2	2
<b>Relevance of the alternative action to</b>	Strategic management	Maximize	1	4	4	4
	Tactical management	Maximize	1	5	5	5
	Emergency management	Minimize	1	1	1	1
<b>Impacts on the management objectives</b>	Water quality	Maximize	1	1	1	1
	Rural water supply	Maximize	1	1	2	2
	Urban water supply	Maximize	1	3	1	1
	Agriculture	Maximize	1	1	3	2
	Hydropower generation	Maximize	1	3	0	2
	Navigation	Maximize	1	1	3	2

Table 4.2.1.1-1: Optimization types and weights of sub-criteria

Criteria	Subcriteria	Pavani Forests Management Alternatives Assessment																				
		Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Alt 7	Alt 8	Alt 9	Alt 10	Alt 11	Alt 12	Alt 13	Alt 14	Alt 15	Alt 16	Alt 17	Alt 18	Alt 19	Alt 20	Alt 21
Feasibility	Costs	High	Low	Medium	Low	Very High	High	Very High	High	High	High	High	High	High	High	High	High	High	High	High	High	High
	Availability of local knowledge	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High
Sustainability	Time to build roads	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High
	Political and Environmental Risk	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High
Development	Opportunity	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High
	Balance of the alternative	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High
Impacts on the	Water Quality	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High
	Urban water supply/demand	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High
Management	Agriculture and Fishing	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High
	Energy generation	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High
Objectives	Restoration	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High
		High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High

Table 4.2.1.1-2: Results of Assessment

#### 4.2.1.1.1. Model application to baseline conditions

For the application of the model to baseline conditions, all criteria and sub-criteria were assigned the same weight. The management alternative actions in the list above are assessed using the criteria and sub-criteria. The assessed qualitative values of the management actions were converted into quantitative ratings and used by compromise programming computation in the EXCEL spreadsheet.

Alternative actions	$p = 1$		$p = 2$		$p = 10$	
	Score	Rank	Score	Rank	Score	Rank
Alternative 1	0.43	7	0.29	4	0.14	2
Alternative 2	0.43	8	0.31	5	0.14	3
Alternative 3	0.57	15	0.46	14	0.34	15
Alternative 4	0.54	14	0.46	15	0.34	14
Alternative 5	0.48	11	0.41	11	0.31	11
Alternative 6	0.41	5	0.31	6	0.18	5
Alternative 7	0.58	16	0.51	16	0.39	17
Alternative 8	0.70	21	0.64	20	0.55	19
Alternative 9	0.60	17	0.51	18	0.38	16
Alternative 10	0.41	6	0.34	8	0.26	10
Alternative 11	0.68	19	0.63	19	0.56	20
Alternative 12	0.60	18	0.51	17	0.41	18
Alternative 13	0.69	20	0.65	21	0.59	21
Alternative 14	0.40	4	0.32	7	0.21	6
Alternative 15	0.47	10	0.37	10	0.23	9
Alternative 16	0.54	13	0.45	13	0.33	12
Alternative 17	0.37	3	0.26	1	0.13	1
Alternative 18	0.34	1	0.29	3	0.22	7
Alternative 19	0.35	2	0.27	2	0.17	4
Alternative 20	0.49	12	0.42	12	0.34	13
Alternative 21	0.46	9	0.35	9	0.23	8

Table 4.2.1.1.1-1: Assessment results for baseline conditions

For all compromise powers ( $p = 1, 2$  &  $10$ ), alternative 17 (Forecasting and monitoring systems) emerges as the most relevant management option; it

ranks third best management option for power 1, and the top option for power 2 and 10. However, to effectively play their role of mitigating drought impacts in tactical terms, forecasting and monitoring systems need to be in place and operational well before drought occurs. Alternative 17 is followed in the ranking by alternative 19 (Regulatory measures.) The ranking of alternative 18 (New large storages) changes from top response-action for power 1 to third and seventh best option for powers 2 and 10 respectively. For all powers of compromise programming, alternative 8 (Diesel powered new rural water distribution system), alternative 11 (Water delivery by individual vendors), alternative 12 (village-level storage reservoir) and 13 (application of rate structure) consistently are ranked at the bottom; therefore, they appear not to be relevant. This ranking contrasts with the common practices, which have made them the first choice for water shortage mitigation. As the power increases, the ranking of alternative 1 (New water wells drilling) and alternative 2 (Water wells rehabilitation) improves from 7 to 2 and from 8 to 3 respectively. The ranking of alternative 5 (New municipal water distribution system) as the 11<sup>th</sup> best management option is not sensitive to the changes in the power of compromise programming.

#### **4.2.1.1.2. Model application with priority order 1**

The management objectives of urban water supply and power generation are assigned the highest priority; the assessment results are given in table 4.2.1.2-1.

Alternative actions	$p = 1$		$p = 2$		$p = 10$	
	Score	Rank	Score	Rank	Score	Rank
Alternative 1	0.44	9	0.31	7	0.13	2
Alternative 2	0.44	7	0.31	6	0.13	3
Alternative 3	0.59	15	0.48	15	0.36	15
Alternative 4	0.53	14	0.45	14	0.35	14
Alternative 5	0.47	11	0.40	12	0.31	11
Alternative 6	0.41	6	0.32	8	0.19	6
Alternative 7	0.61	16	0.54	16	0.41	16
Alternative 8	0.73	21	0.68	21	0.59	19
Alternative 9	0.63	17	0.55	17	0.41	17
Alternative 10	0.38	5	0.30	5	0.22	9
Alternative 11	0.72	20	0.68	20	0.62	21
Alternative 12	0.63	18	0.55	18	0.45	18
Alternative 13	0.70	19	0.67	19	0.61	20
Alternative 14	0.37	4	0.29	3	0.19	5
Alternative 15	0.48	12	0.38	10	0.25	10
Alternative 16	0.53	13	0.45	13	0.34	13
Alternative 17	0.36	3	0.26	2	0.15	4
Alternative 18	0.35	2	0.30	4	0.22	8
Alternative 19	0.28	1	0.21	1	0.12	1
Alternative 20	0.45	10	0.38	11	0.32	12
Alternative 21	0.44	8	0.33	9	0.20	7

Table 4.2.1.1.2-1: Results of model application for priority order 1

With a few exceptions, the major trends observed in the ranking of the options for the baseline are also present in their ranking for this priority order. Like before, alternative 19 (Regulatory measures), which is both a strategic, tactical and emergency measure, is ranked at the top for all powers of compromise programming. Alternative 18 (New large reservoir), which is a strategic management action, is ranked second for power 1, fourth for power two and eighth for power 10. For the rest, the pattern of changes in the ranking for different powers of compromise programming is very similar to what was already observed with the baseline conditions.

#### **4.2.1.1.3 Model application with priority order 2**

Again, for all powers of CP, alternative 19 (Regulatory measures) is ranked at the top. By dropping significantly in the ranking, alternatives 10 and 18 proved to be sensitive to the increase in the power of compromise programming. They are also less relevant to the mitigation of drought impacts for this priority order. That alternative 1 (Water wells drilling) and alternative 2 (Water wells rehabilitation) rank high is consistent with their common use as mitigation actions. However, they have little if any impact, on the management objectives, which are given the highest priority.

Like in previous cases, here too, the ranking of some management options at the bottom is not consistent with their being among the first choices for mitigation. This inconsistent ranking is particularly true for:

- ✓ Alternative 7 (New rural water distribution system—solar energy powered);
- ✓ Alternative 8 (New rural water distribution system--diesel powered);
- ✓ Alternative 9 (Rehabilitation of rural water distribution systems);
- ✓ Alternative 11 (Water delivery by individual vendors);
- ✓ Alternative 12 (Village-level storage reservoir), and;
- ✓ Alternative 13 (Application of pricing rate structure).

Alternative actions	$p = 1$		$p = 2$		$p = 10$	
	Score	Rank	Score	Rank	Score	Rank
Alternative 1	0.44	8	0.32	6	0.15	3
Alternative 2	0.44	7	0.32	5	0.15	4
Alternative 3	0.57	15	0.46	14	0.34	12
Alternative 4	0.54	14	0.47	15	0.37	15
Alternative 5	0.51	12	0.44	12	0.35	13
Alternative 6	0.45	9	0.36	9	0.23	8
Alternative 7	0.59	18	0.52	18	0.39	18
Alternative 8	0.71	20	0.66	19	0.57	19
Alternative 9	0.59	17	0.51	17	0.37	16
Alternative 10	0.39	5	0.32	7	0.24	9
Alternative 11	0.73	21	0.69	21	0.64	21
Alternative 12	0.58	16	0.50	16	0.39	17
Alternative 13	0.70	19	0.67	20	0.61	20
Alternative 14	0.36	4	0.28	3	0.19	5
Alternative 15	0.47	11	0.37	10	0.25	10
Alternative 16	0.54	13	0.46	13	0.36	14
Alternative 17	0.35	3	0.26	2	0.15	2
Alternative 18	0.34	2	0.30	4	0.22	7
Alternative 19	0.27	1	0.20	1	0.12	1
Alternative 20	0.46	10	0.40	11	0.34	11
Alternative 21	0.43	6	0.32	8	0.20	6

Table 4.2.1.1.3-1: Results of model application for priority order 2

For alternatives 7, 8 and 9, their high costs in terms of investment, operation and maintenance may have contributed to their low ranking. For the most part, the implementation of these options is funded by external sources. Due to their poor design and implementation, village-level reservoirs (alternative 12) have not been reliable enough to be relevant to drought mitigation.

#### 4.2.1.1.4. Model application with priority order 3

The results are identical to those of the previous priority orders, except for alternatives 7, 9 and 12, which are all relative to the only management objective of rural water supply. However, due to their ranking, and despite

the extensive resorting to them in actual mitigation, these alternative options seem not to be relevant enough to be of first choice.

Alternative actions	$p = 1$		$p = 2$		$p = 10$	
	Score	Rank	Score	Rank	Score	Rank
Alternative 1	0.44	8	0.32	6	0.15	3
Alternative 2	0.44	7	0.32	5	0.15	4
Alternative 3	0.57	15	0.46	14	0.34	12
Alternative 4	0.54	14	0.47	15	0.37	15
Alternative 5	0.51	12	0.44	12	0.35	13
Alternative 6	0.45	9	0.36	9	0.23	8
Alternative 7	0.59	16	0.52	16	0.39	16
Alternative 8	0.71	20	0.66	19	0.57	19
Alternative 9	0.61	18	0.53	18	0.39	17
Alternative 10	0.39	5	0.32	7	0.24	9
Alternative 11	0.73	21	0.69	21	0.64	21
Alternative 12	0.60	17	0.52	17	0.41	18
Alternative 13	0.70	19	0.67	20	0.61	20
Alternative 14	0.36	4	0.28	3	0.19	5
Alternative 15	0.47	11	0.37	10	0.25	10
Alternative 16	0.54	13	0.46	13	0.36	14
Alternative 17	0.35	3	0.26	2	0.15	2
Alternative 18	0.34	2	0.30	4	0.22	7
Alternative 19	0.27	1	0.20	1	0.12	1
Alternative 20	0.46	10	0.40	11	0.34	11
Alternative 21	0.43	6	0.32	8	0.20	6

Table 4.2.1.1.4-1: Results of model application for priority order 3

#### 4.2.1.2. Model sensitivity to drought severity

As suggested before, due to the potential for a drought event to develop into different scenarios, there is a need for the management to define an adaptive strategy.

Alternative Actions	Drought Scenarios							
	Drought Start/End		Mild drought		Severe drought		Crisis	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank
<b>Alt 1</b>	0.43	8	0.43	7	0.43	7	0.43	8
<b>Alt 2</b>	0.43	9	0.43	8	0.43	8	0.43	9
<b>Alt 3</b>	0.55	14	0.57	15	0.59	15	0.61	16
<b>Alt 4</b>	0.54	13	0.54	14	0.54	14	0.54	14
<b>Alt 5</b>	0.47	10	0.49	11	0.51	12	0.53	13
<b>Alt 6</b>	0.41	5	0.41	5	0.41	5	0.41	5
<b>Alt 7</b>	0.57	17	0.59	17	0.61	18	0.63	18
<b>Alt 8</b>	0.68	19	0.70	21	0.72	21	0.74	21
<b>Alt 9</b>	0.60	18	0.60	18	0.60	17	0.60	15
<b>Alt 10</b>	0.41	6	0.41	6	0.41	6	0.41	6
<b>Alt 11</b>	0.69	20	0.67	19	0.65	19	0.63	19
<b>Alt 12</b>	0.56	16	0.58	16	0.60	16	0.62	17
<b>Alt 13</b>	0.70	21	0.68	20	0.66	20	0.64	20
<b>Alt 14</b>	0.40	4	0.40	4	0.40	4	0.40	4
<b>Alt 15</b>	0.48	11	0.46	10	0.44	9	0.42	7
<b>Alt 16</b>	0.55	15	0.53	13	0.51	13	0.49	11
<b>Alt 17</b>	0.37	3	0.37	3	0.37	3	0.37	2
<b>Alt 18</b>	0.33	1	0.35	1	0.37	2	0.39	3
<b>Alt 19</b>	0.35	2	0.35	2	0.35	1	0.35	1
<b>Alt 20</b>	0.49	12	0.49	12	0.49	11	0.49	11
<b>Alt 21</b>	0.41	7	0.43	9	0.45	10	0.47	10

Table 4.2.1.2-1: Compromise programming ( $p = 1$ ) results for the Baseline

Therefore, the model was also applied to the baseline conditions for all the potential development phases of a drought event and for power 1 of compromise programming.

For all severity levels, alternatives 6, 10 and 14 remain at the same position in the ranking, respectively as fifth, sixth and fourth best management options. This steady ranking among the top options means that they are relevant to all the management phases. For the two less severe levels, the

strategic management alternative 18 (New storage) is ranked as best management action; for the most severe levels it drops to second and third best option, meaning that it is not relevant to the tactical and emergency management. Ranked second best for phases 1 & 2, Alternative 19 (Regulatory measures) goes to the top for the crisis and emergency levels, which confirms its relevance to all phases of a developing drought. As shown by the ranking at different severity levels, some of the management alternatives widely implemented, such as alternatives 7, 8, 9, 11 and 13, have proven ineffective.

Overall, the changes in the ranking of alternative options for the four scenarios may help identify four categories:

- ✓ The management options maintaining the same ranking for all drought scenarios, meaning that they are consistently relevant if ranked high or not relevant if they are ranked low. Alternatives 6, 10 and 14 are representative of this trend;
- ✓ The management options moving consistently downward in the ranking as the severity increases. This category of management options, represented by alternatives 3, 4, 5, 6, 8, 9, 12, 18 and 21, become less and less relevant to the management objectives, and no matter what their initial ranking might be;

Alternative Management Actions	Sensitivity of Ranking to drought intensity				
	Baseline	Drought Start/End	Mild drought	Severe drought	Crisis
Alternative 1	7	8	7	7	8
Alternative 2	8	9	8	8	9
Alternative 3	15	14	15	15	16
Alternative 4	14	13	14	14	14
Alternative 5	11	10	11	12	13
Alternative 6	5	5	5	5	5
Alternative 7	16	17	17	18	18
Alternative 8	21	19	21	21	21
Alternative 9	17	18	18	17	15
Alternative 10	6	6	6	6	6
Alternative 11	19	20	19	19	19
Alternative 12	18	16	16	16	17
Alternative 13	20	21	20	20	20
Alternative 14	4	4	4	4	4
Alternative 15	10	11	10	9	7
Alternative 16	13	15	13	13	11
Alternative 17	3	3	3	3	2
Alternative 18	1	1	1	2	3
Alternative 19	2	2	2	1	1
Alternative 20	12	12	12	11	11
Alternative 21	9	7	9	10	10

Table 4.2.1.2-2: Ranking summary table

- ✓ The management actions moving consistently upward in the ranking meaning an increasing relevance of the alternative options;
- ✓ The management options with upward and downward changes in their ranking; alternatives 1 & 2 represent this category.

All these trends evidence the sensitivity of the model to drought severity level, which exactly what it was supposed to be.

From the results of compromise programming ( $p = 1$ ) for all drought scenarios, it appears that the best strategy for managing the impacts would

require the combination of the alternative options of all the three types: strategic, tactical, and emergency measures.

The results of such an assessment may be used for:

- ✓ Water resources planning and management, in which case, the ranking of the alternatives option may provide the basis for selecting the most relevant management strategy;
- ✓ Actual drought impacts management, in which case, any ongoing strategic will be scaled back to leave the way for the tactical management designed on the ranking of the alternatives available.

#### **4.2.2. WATER SUPPLIES AND DEMANDS MANAGEMENT FOR A COLORADO CITY, USA**

For comparison, the model was applied to the case of a city in Colorado, USA. Since the application was solely for the purpose of comparison in this study, the actual name of the City is not to be disclosed.

##### **4.2.2.1. Generality**

The City is located on the foothills of the Rocky Mountains and in basin of the Cache La Poudre River, Colorado. With an annual average total precipitation of 14.4 inches, the City, like the rest of Colorado, has a semi-arid climate on the eastern slope of the Rocky Mountains.

The estimate of the total population is over 100,000 persons with an annual growth of 2.9%; the annual median income of a four-person household is around \$60,000.

To meet water demand of its population and businesses, the City gets water supplies from different sources, including the Cache La Poudre River. To anticipate the potential impacts of drought on those water sources, the USA City has defined and implemented its *Water supply and demand management policy* and a *Water Shortage Response Plan* as mitigation tools. In order to implement the policy and the response plan, the problem for water resources managers is to select the most relevant mitigation actions, and define the timing and sequencing of their implementation.

#### **4.2.2.2. USA City Water Supplies and Demand Management**

The USA City receives waters supplies from different sources, including The Colorado Big Thomson (CBT) project.

The Water Supply Policy adopted by the City in 1998 provides that its water supply from these sources must be reliable enough to withstand a drought event with a 50-year return period. For more severe droughts, the City must resort to demand reduction by a series of restrictions on water uses, as defined by the "*Water Supply Shortage Response Plan.*" In extension, the City is in the process of defining a "*Water supply and Demand Management Policy,*" which combines the policy objectives of the two documents

mentioned previously. This effort has the goal of developing the integrated management of water supply and demand in order to ultimately achieve sustainability. If adopted, this comprehensive policy will increase the readiness of the City for dealing with the potential impacts of droughts, or other disruptions of its supply sources. The proposed policy is summarized as follows:

#### **4.2.2.2.1. Water Demand Management**

Through conservation, the new policy has the objective of reducing, by the year 2010, water use to an average volume of 195 gallons per capita per day (gpcd), and the peak demand to 502 gpcd. To achieve this objective, the policy provides the following management actions:

- ✓ Educational programs designed to raise public awareness about efficient water use;
- ✓ Rate structures, which consist of incremental pricing for increased water use;
- ✓ Incentive programs designed to provide water users with assistance for upgrading their installations to avoid wasting water;
- ✓ Regulatory measures promoting water use efficiency;
- ✓ Operational measures, which are aimed at reducing water losses in public facilities.

#### **4.2.2.2.2. Water Supply**

As mentioned before, the objective of water supply management is to maintain the reliability of the system in case of a 50-year return period drought occurs in the Cache La Poudre River basin. To achieve this objective, the City keeps acquiring water rights and developing new water storage capacities. It also requires that new developers provide water rights or cash at least equivalent to the volume of water to be used in the development area. In case the supply exceeds the demand, the City trades the surplus with other entities in need. Water rental market price that allows the City to recover the cost of owning the supply surplus provides the basis for the transaction. On average, the City delivers a total annual volume of 32,100 acre-feet of treated water and 7000 to 8000 acre-feet of raw water.

#### **4.2.2.2.3. Water Supply Shortage Response Plan**

This "Water Supply Response Plan" is an emergency management tool designed to deal with exceptionally severe water shortages. It consists mainly of four types of measures:

- ✓ Restrictions for different water uses;
- ✓ Enforcement measures;
- ✓ Water rate adjustments;
- ✓ Acquisition of additional supplies as temporary supplements.

#### **4.2.2.2.4. Regional Cooperation**

In terms of regional cooperation, the City and its neighboring providers of water supply services have the objectives of defining and implementing consistent policies for the management of water shortages. To achieve these objectives of common interest, they may undertake activities such as:

- ✓ Studying, building and sharing water conveyance facilities, distribution networks, and storage capacities with other providers of municipal water supply services for mutual assistance.
- ✓ The transfer, exchange, and use of water resources of the Cache La Poudre River between the City and local irrigation companies;
- ✓ The transfer of water rights from agricultural to municipal use during periods of water shortages.

#### **4.2.2.2.5. Raw Water Quality**

To implement its Drinking Water Quality Policy, the City plays a proactive role in the protection of the sources of its water supplies.

#### **4.2.2.2.6. Streamflow Requirements**

To the limits of its obligations for providing its inhabitants and businesses with adequate water supply services, the City and other stakeholders have committed themselves to the fulfillment of the instream flow requirements of the Cache La Poudre River. The requirements may be related to ecosystem protection, recreation, or aesthetics.

#### **4.2.2.3. Model application**

The City is chosen as a case study of the model application in order to explore the performance of the model in terms of reflecting the contrast between the mitigation of drought impacts in a non-developed African country and that in an industrialized society like that of this USA City.

##### **4.2.2.3.1. Management objectives**

As mentioned earlier, the ultimate objective of defining and implementing the alternative measures is to provide the City with a water supply service, which can withstand a drought with a 50-year return period. As stated in the policy objective of the new "Water Supply and Demand Management Policy," the City plans to use a sustainable and integrated approach in order to:

- ✓ Provide its customers with an adequate and reliable water supply service;
- ✓ Achieve efficiency in water use through demand management.

##### **4.2.2.3.2. Management alternative options**

With the assistance of water resources engineers of the Water Resources Division (The City Utilities) to this study, the alternative options for managing water shortage were identified in the new policy as follows:

- ✓ Alternative 1: Educational programs;
- ✓ Alternative 2: Rate Structures;

- ✓ Alternative 3: Incentive Programs;
- ✓ Alternative 4: Regulatory Measures;
- ✓ Alternative 5: Operational Measures;
- ✓ Alternative 6: Raw Water Requirements;
- ✓ Alternative 7: Storage Capacity;
- ✓ Alternative 8: Restrictions on water uses
- ✓ Alternative 9: Acquisition of Additional Supplies

#### **4.2.2.3.3. Assessment Results**

Using the criteria and subcriteria of the model, the nine alternative management options listed above were assessed by the water resources engineer of the City. For this engineer, the issue was to consider the options individually, and, with regard to each criterion and sub-criterion, to assign the most likely attribute in the specific context of the City; the results are shown in the table below:

Criteria	Subcriteria	Optimiz.	Assessment of Drought Impacts Management Alternative Measures								
			Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Alt 7	Alt 8	Alt 9
<b>Feasibility</b>	Costs	Min	Medium	Medium	High	Low	High	Low	Very high	Medium	Very high
	Availability of Funding	Max	Good	Good	Poor	Good	Poor	Good	Good	Fair	Poor
	Availability of local expertise	Max	Excellent	Excellent	Good	Good	Good	Good	Good	Good	Good
	Time to raise funds	Min	Average	Short	Very Long	Average	Very Long	Short	Very Long	Average	Long
	Mobiliz. And Implement. Time	Min	Average	Average	Long	Long	Long	Short	Very Long	Short	Average
<b>Sustainability</b>	Prospect for costs Recovery	Max	Poor	Good	Good	Good	Good	Excellent	Good	Fair	Poor
	Non-Structural Adaptability	Max	Excellent	Excellent	Good	Excellent	Fair	Good	Good	Poor	Good
	Reliability	Max	Medium	High	High	High	High	High	Very high	High	High
	Avail. of expertise for O&M	Max	Excellent	Excellent	Good	Good	Good	Good	Excellent	Good	Good
	Structural Adaptability	Max	None	None	Good	None	Fair	None	Good	None	None
<b>Development</b>	Opport. for phased develop.	Max	Good	Excellent	Excellent	Good	Good	None	Poor	Good	Poor
	Local Impacts	Max	Positive	Indifferent	Positive	Positive	Positive	Indifferent	Indifferent	Positive	Positive
<b>Opportunity</b>	Potential Poverty reduction	Max	None	None	None	None	None	None	None	None	None
	Political sensitivity	Min	Low	Very high	Medium	High	Low	Medium	Very high	Very high	High
	Basinwide Impacts	Max	Positive	Positive	Positive	Positive	Positive	Indifferent	Positive	Positive	Indifferent
<b>Relevance of The alternative Action to</b>	The strategic Management	Max	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
	The tactical Management	Max	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
	Emergency Management	Min	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes
<b>Impacts on the Management Objectives</b>	Water Quality	Max	Positive	Indifferent	Indifferent	Indifferent	Positive	Indifferent	Indifferent	Indifferent	Indifferent
	Rural water supply	Max	Positive	Positive	Positive	Positive	Positive	Negative	Positive	Indifferent	Negative
	Urban water supply & sanitat.	Max	Positive	Positive	Positive	Positive	Positive	Positive	Very Positive	Positive	Positive
	Agriculture and Fishing	Max	Positive	Positive	Positive	Positive	Indifferent	Negative	Positive	Indifferent	Negative
	Energy generation	Max	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent
	Navigation	Max	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent

Table 4.2.2.3.3-1: Results of the qualitative assessment by the City water resources engineer

From the results of this qualitative assessment, three particular situations are noticeable:

- ✓ For sub-criterion "Potential for Poverty Reduction" under the criterion "Development opportunity," the "None" answers for all nine options seems to indicate that this sub-criterion is irrelevant in the case of the City. The reason might be that, in this city, given the structure of the economy, the extent of water availability has no bearing on the level of revenues of its inhabitants. In contrast, for most people in non-developed countries, the access to water may be a determinant factor in the economic status;
- ✓ The "indifference" of all alternative options to the management objectives of "Power generation" and "Navigation" is reflective of the absence of any of these activities in all the areas providing supplies to the City. This is mainly due to the geographic location of the city, the sources of its water supplies, and water right governing those supplies.

For the reasons given above, the three criteria were eliminated from further consideration in the case study. As was explained earlier, the next step in the model application is to convert the qualitative assessment into quantitative values as shown the Table 4.2.2.3.3-2.

Criteria	Subcriteria	Optimiz.	Assessment of Drought Impacts Management Alternative Measures								
			Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Alt 7	Alt 8	Alt 9
Feasibility	Costs	Min	3	3	2	4	2	4	1	3	1
	Availability of Funding	Max	4	4	2	4	2	4	4	3	2
	Availability of local expertise	Max	5	5	4	4	4	4	4	4	4
	Time to raise funds	Min	3	4	1	3	1	4	1	3	2
	Mobiliz. And Implement. Time	Min	3	3	2	2	2	4	1	4	3
Sustainability	Prospect for costs Recovery	Max	2	4	4	4	4	5	4	3	2
	Non-Structural Adaptability	Max	5	5	4	5	3	4	4	2	4
	Reliability	Max	3	4	4	4	4	4	5	4	4
	Avail. of expertise for O&M	Max	5	5	4	4	4	4	5	4	4
	Structural Adaptability	Max	1	1	4	1	3	1	4	1	1
Development	Opport. for phased develop.	Max	4	5	5	4	4	1	2	4	2
	Local Impacts	Max	4	3	4	4	4	3	3	4	4
	Potential Poverty reduction	Max	1	1	1	1	1	1	1	1	1
Opportunity	Political sensitivity	Min	4	1	3	2	4	3	1	1	2
	Basinwide Impacts	Max	4	4	4	4	4	3	4	4	3
Relevance of The alternative action to	Strategic Management	Max	2	2	2	2	2	2	2	1	1
	Tactical Management	Max	2	2	2	2	2	1	2	2	2
	Emergency Management	Min	1	1	2	1	2	2	1	1	1
Impacts on the Management	Water Quality	Max	4	3	3	3	4	3	3	3	3
	Rural water supply	Max	4	4	4	4	4	2	4	3	2
Objectives	Urban water supply & sanitat.	Max	4	4	4	4	4	4	5	4	4
	Agriculture and Fishing	Max	4	4	4	4	3	2	4	3	2
	Energy generation	Max	3	3	3	3	3	3	3	3	3
	Navigation	Max	3	3	3	3	3	3	3	3	3

Table 4.2.2.3.3-2: Conversion of qualitative attributes into quantitative values

The evaluation of these quantitative values by the MCDA technique of compromise programming resulted in the scores and ranking of the alternatives as shown in Table 4.2.2.3.3-3, below. At this stage of the assessment, all criteria were assigned the same weight, and except for the strategic, tactical, and emergency management whose weights vary with water shortage severity, all other subcriteria were assigned equal weight.

Management Options	Performance and ranking of alternative options at different levels of water shortage severity									
	Normal Conditions		Drought Start/End		Mild Drought		Severe Drought		Crisis	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Alt 1	0.28	3	0.28	3	0.28	3	0.28	3	0.28	3
Alt 2	0.27	2	0.27	2	0.27	2	0.27	2	0.27	2
Alt 3	0.29	4	0.31	4	0.33	5	0.35	5	0.37	5
Alt 4	0.32	6	0.32	5	0.32	4	0.32	4	0.32	4
Alt 5	0.32	5	0.34	6	0.36	6	0.38	6	0.40	6
Alt 6	0.55	7	0.67	9	0.69	9	0.71	9	0.73	9
Alt 7	0.17	1	0.17	1	0.17	1	0.17	1	0.17	1
Alt 8	0.63	8	0.51	7	0.49	7	0.47	7	0.45	7
Alt 9	0.69	9	0.57	8	0.55	8	0.53	8	0.51	8

Table 4.2.2.3.3-3: Results of Compromise Programming ( $p = 1$ )

Comparison of the ranking of the alternative options at different severity levels of water shortage can help identify three groups, each, characterized by a specific trend:

- ✓ The first group, which includes Storage capacity (alternatives 7), Rate structures (alternative 2) and Educational Programs (alternative 1,) is characterized by a constant score and subsequently, by an unchanged ranking at all stages. Coincidentally, these options ranked first, second and third best alternative actions for mitigation. This ranking of alternative 7 is consistent with the conclusions of the study, which assessed the future water supplies, and demands of the City (The City Utilities Annual Operating Report, 2002.) The constant ranking of Rate Structures (Alternative 2) as the second best option, and that of Educational Programs (Alternative 1) as third best alternative prove that for the mitigation of water shortage, measures other than those of supply augmentation (Storage Capacity) have to be given a greater

consideration. It also suggests the crucial importance of the strategic implementation of the Rate Structure (Alternative 2) along with the two other options of this group for achieving the long-term water conservation goals as stated in the new policy.

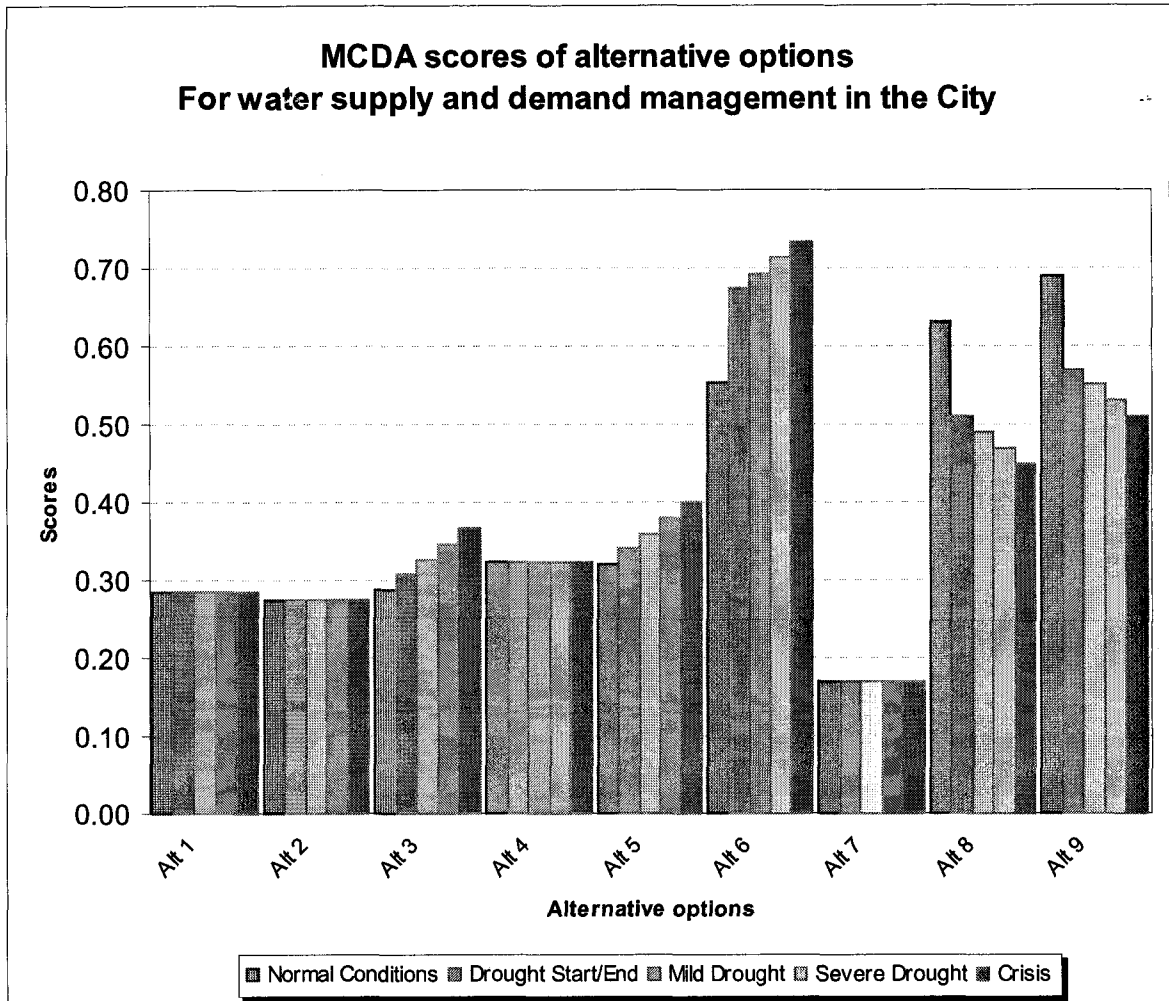


Figure 4.2.2.3.3-1: Performance scores of management options

- ✓ The second group, which includes "Incentive Programs" (alternative 3), "Operational Measures" (alternative 5), and "Raw Water requirements" (alternative 6) is characterized by a decrease in the ranking as the shortage worsens. The change in ranking suggests a

sensitivity, which reflects a decreasing relevance to the mitigation; as the shortage intensifies, they become less relevant.

- ✓ The third group is made of alternative 4 (Regulatory Measures,) alternative 8, (Restrictions on Water Uses) and alternative 9 (Acquisition of Additional Supplies.) The management options of this group are characterized by an improvement in their rankings, which reflects an increased relevance to the mitigation of a worsening water shortage. Both alternatives 8 and alternative 9 move up in the ranking by just one unit, which does little to improve their viability, given their initial ranking at the bottom. The low ranking of alternative 8 (Restrictions on Water Uses) is not consistent with the conclusions of the 2002 Annual Operating Report of the City Utilities, which attributed the 7% saving of water to the only restrictions. This inconsistency may be explained by the fact that actual water savings result from the combined effect of the implemented management options rather than the only restrictions on water uses as suggested by the report. The improvement in the ranking of alternative 4, moving up from rank 6 under normal conditions to rank 5 (at the Start/End phase of water shortage,) and to rank 4 for the most severe levels, is the most significant. This improvement of the ranking makes of alternative 4 the most sensitive to the developments in water shortage.

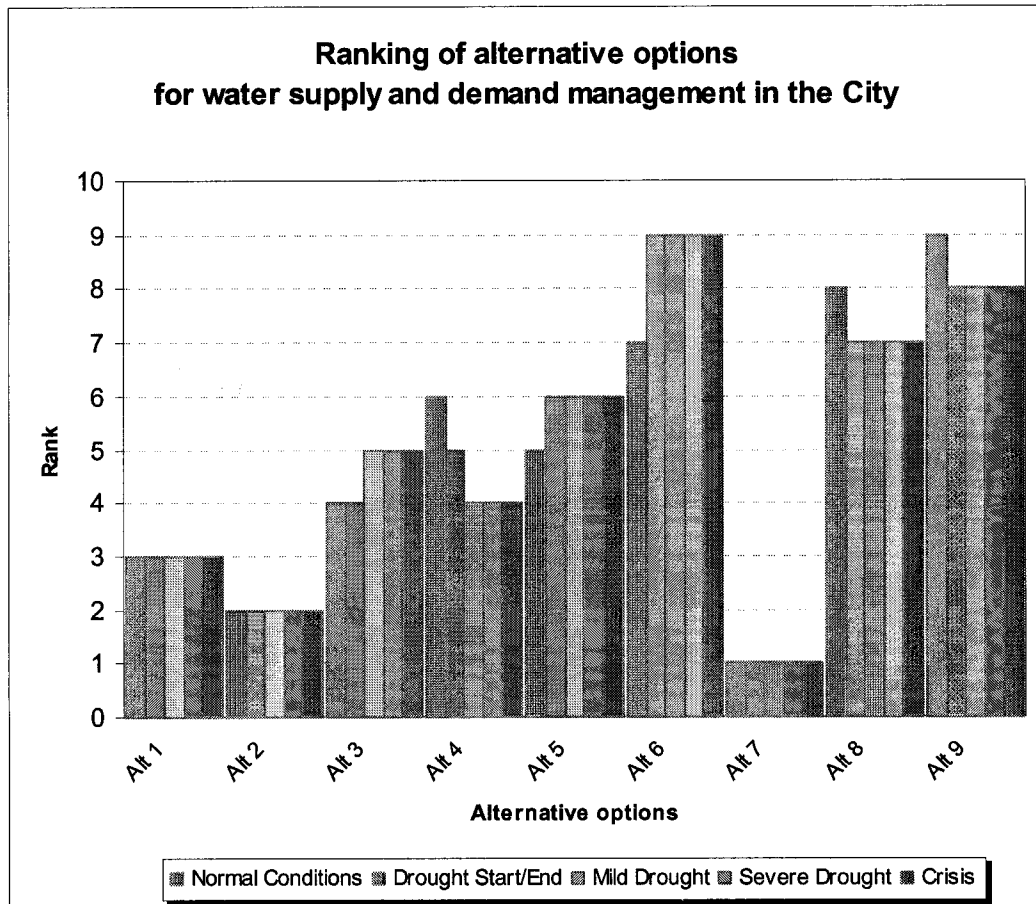


Figure 4.2.2.3.3-2: Ranking scores of management options

#### 4.2.2.3.4. Relevance and Sustainability Index

The scores computed by the MCDA technique (Compromise Programming in this case) are converted into Relevance and Sustainability Indices by the following formula:

Relevance and Sustainability Index:  $RSI = 1 - L_{mj}$ , where  $L_{mj}$  is the MCDA score.

The values of the RSI of the nine alternative options are given in the table and plotted in the graph below.

Management Options	Relevance and Sustainability Index and Ranking of Alternative Options at Different Levels of Water Shortage Severity									
	Normal Conditions		Drought Start/End		Mild Drought		Severe Drought		Crisis	
	RSI	Rank	RSI	Rank	RSI	Rank	RSI	Rank	RSI	Rank
Alt 1	0.72	3	0.72	3	0.72	3	0.72	3	0.72	3
Alt 2	0.73	2	0.73	2	0.73	2	0.73	2	0.73	2
Alt 3	0.71	4	0.69	4	0.67	5	0.65	5	0.63	5
Alt 4	0.68	6	0.68	5	0.68	4	0.68	4	0.68	4
Alt 5	0.68	5	0.66	6	0.64	6	0.62	6	0.60	6
Alt 6	0.45	7	0.33	9	0.31	9	0.29	9	0.27	9
Alt 7	0.83	1	0.83	1	0.83	1	0.83	1	0.83	1
Alt 8	0.37	8	0.49	7	0.51	7	0.53	7	0.55	7
Alt 9	0.31	9	0.43	8	0.45	8	0.47	8	0.49	8

Table 4.2.2.3.4-1: RSI and ranking of alternative options

While the best alternatives have the lowest MCDA scores, they get the highest SRI values, which make the results much easy to understand; the SRI values are plotted in the graph below.

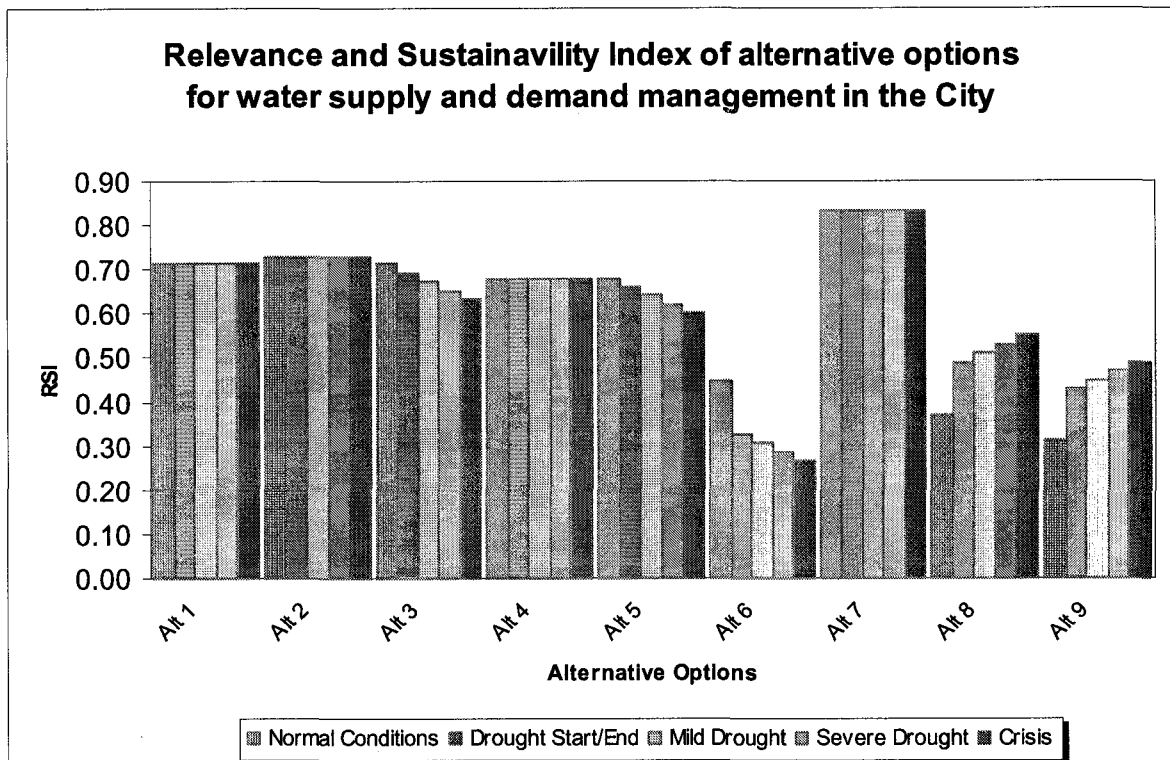


Figure 4.2.2.3.4-1: Relevance and Sustainability Index of alternative options

As mentioned earlier, the criteria and sub-criteria (except the relevance of the options to the strategic, tactical and emergency management) were assigned equal weights for this assessment.

For comparison, the alternative options were assessed a second time with different weights assigned to the criteria and sub-criteria. The weights, as shown in the table below, were assigned by the same city water engineer who rated the alternative options. By these weights, the Water Resources Division of the USA City Utilities defines the priority order for the criteria and sub-criteria in order to achieve its long-term objectives of water shortage management.

<b>Criteria</b>	<b>Weight</b>	<b>Subcriteria</b>	<b>Weight</b>
<b>Feasibility</b>	3	Costs	3
		Availability of Funding	3
		Availability of local expertise	1
		Time to raise funds	2
		Mobiliz. And Implement. Time	1
<b>Sustainability</b>	2	Prospect for costs Recovery	2
		Non-Structural Adaptability	2
		Reliability	3
		Avail. of expertise for O&M	1
		Structural Adaptability	2
<b>Development Opportunity</b>	2	Opport. for phased develop.	2
		Local Impacts	3
		Potential Poverty reduction	0
		Political sensitivity	3
		Basinwide Impacts	2
<b>Relevance of The alternative Action to</b>	2	The strategic Management	5
		The tactical Management	3
		Emergency Management	2
<b>Impacts on the Management Objectives</b>	1	Water Quality	3
		Rural water supply	2
		Urban water supply & sanitation	3
		Agriculture and Fishing	2
		Energy generation	0
		Navigation	0

Table 4.2.2.3.4-2: Priority order of criteria and sub-criteria

With these weights assigned to the criteria and sub-criteria, the results of the assessment are given in the following table.

Management Options	Relevance and Sustainability Index and Ranking of Alternative Options at Different Levels of Water Shortage Severity	
	RSI	Rank
Alt 1	0.64	3
Alt 2	0.66	2
Alt 3	0.62	5
Alt 4	0.64	4
Alt 5	0.59	6
Alt 6	0.31	9
Alt 7	0.82	1
Alt 8	0.45	7
Alt 9	0.41	8

Table 4.2.2.3.4-3: Results of the model application with the priority order defined by the engineer

The resulting ranking is identical to that obtained for the three worst scenarios of water shortage by the first assessment. Compared to that of the first assessment for normal conditions, this ranking is different for all alternatives, except for the three best options. Alternative 6 (Raw Water Requirement) is an illustration of this situation where the first and second assessments rank it respectively 7<sup>th</sup> and 9<sup>th</sup> best option.

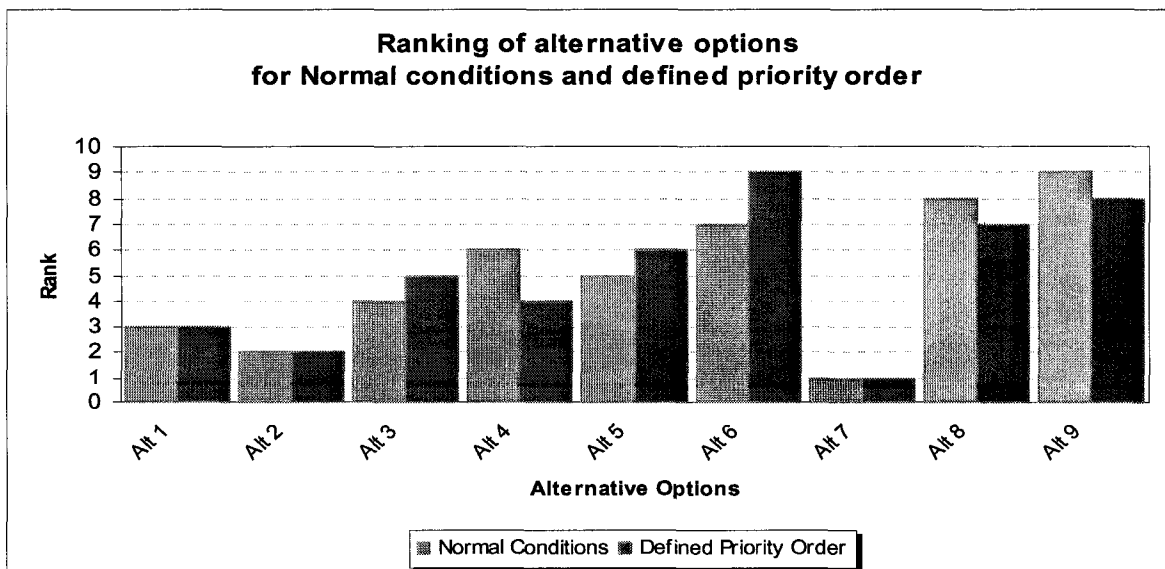


Figure 4.2.2.3.4-2: Ranking of options for the strategic management

### **4.2.3. Discussion of Results**

The comparison of the results suggests a number of similarities and contrasts between the contexts of the two applications of the model. Therefore, the model, if refined, may be applicable to whatever situation needs to.

For the case study in Mali, the model was applied to a series of potential management actions, which for the most part have already been implemented in previous efforts of drought mitigation. The results of the assessment proved, as anticipated, that the model worked well for identifying and ranking the most relevant management actions for different priority orders of the management objectives or for drought severity levels. Each of the applications of the model has produced a unique ranking of the management options. From the beginning of drought to crisis, changes observed in the ranking of the alternative options can help identify three main patterns:

- ✓ The management options moving up in the ranking are those becoming increasingly relevant to the tactical and emergency mitigation. Alternative 15 (Conditional reservoir operation), alternative 16 (Prioritizing water uses) and alternative 13 (application of pricing rate structure) and others fall into this category;
- ✓ The management options moving down in the ranking are those becoming increasingly less relevant to the tactical and emergency mitigation. Alternative 21 (Drought early detection and warning), alternative 18 (New large storages) and others fall into this category;

- ✓ The management options, maintaining consistently their initial ranking or making small changes in either direction, are those insensitive to the severity levels. They may be relevant if they are ranked high and not relevant if ranked low;

The three patterns described above provide an informed basis for defining a consistent operational strategy. The management options not sensitive to the tactical and emergency management are those to consider for the strategic management if they rank high. The alternative options that are increasingly sensitive to drought severity may be the best choice for the tactical and emergency management, depending on their ranking. Those of the third category may be good candidates for any management stage, depending on their steady ranking.

Despite their extensive use for mitigation, the ranking of some of the alternative actions has proved that they might not be the best choices in terms of relevance and sustainability. Alternative 11 (water delivery by individual vendors) and alternative 8 (diesel powered new rural water distribution system) are among the mitigation options, which appear to be implemented by preference rather than by performance.

Based on these results, the application of the model has produced an assessment consistent with the actual performance of the alternative options in the field. However, it is important to notice the contrast between the management strategy resulting from the assessment and current practices,

which seem to favor decision-makers' preference over the anticipated performance of the management options. Therefore, the need for an effective mitigation and optimal allocation of the resources call for assessment framework, which can help define the timing and sequencing of the management options most relevant to the mitigation of drought impacts.

The model was also applied to the case study of a city in the USA in order to test its applicability to the situation of an industrialized society and identify any contrast with the results of the first application. In terms of applicability, the results have shown that the model can perform well in the settings of a developed country. Like the assessment in Mali, the results of this application have produced similar patterns of changes in the ranking at different levels of drought severity:

- ✓ The category of alternative options with increasing relevance consists of alternative 4 (Regulatory measures), alternative 8 (Restrictions on water uses) and alternative 9 (Acquisition of additional supplies). Despite the improving ranking of alternatives 8 and 9, their overall poor performance make them less preferable candidates for an operational strategy;
- ✓ The category of alternative options with decreasing relevance is made of alternative 3 (Incentive programs), alternative 5 (Operational measures) and alternative 6 (Raw water requirement). Except for alternative 3, the low ranking of the two other options of this category makes them less relevant anyway.

- ✓ Alternative 7 (Storage capacity), alternative 1 (Educational programs) and alternative 2 (Rate structures) form the third category of options maintaining the same high position in the ranking for all levels of drought severity; by all accounts, they are relevant to all stages of mitigation.

For this city the overall management strategy will consist of implementing alternative 7 in strategic term, alternative 1 and 2 in strategic, tactical and emergency terms; the other options may be implemented in following priority order: alternatives 3, 4, 5, 6, 8 and 9.

The results have also shown some contrasts between the situation in Mali and that of the City in the USA. The main differences include the fact that:

- ✓ Certain sub-criteria, such as "Potential poverty reduction" might not be relevant to developed countries where, the access to water supply services seems not to have any bearing on the economic status;
- ✓ Due to the availability of financial resources and expertise in the City, the criteria of feasibility and sustainability and their sub-criterions are not a big issue as opposed to the constraints they can be in poor countries;
- ✓ While the model is applied to the generic set of management objectives in Mali, the application to the City in the USA is focused on water supply, which is the only relevant management objective;
- ✓ Despite the low ranking of the option "Restriction on water uses" in both applications, it is worth noting the fundamental difference

between the potential effects of the application of this option in the two contexts. In the USA City, the application of the management option "Restriction on water uses" is targeting the outdoor uses of lawn and turf watering, not indoor uses. As such, this may result in a reduction of the comfort level of domestic water users, while their basic needs are still being met. In a non-developed context where the provision of water supply services is, for most users, limited to the basic water needs, there is no room for restriction.

In terms of similarities, it is important to notice that while the management options may be different, the problems posed by water shortages are of the same nature in both developed and non-developed countries. In addition, the results of both applications show that for an effective drought impacts management:

- ✓ It is imperative to combine all three types (strategic, tactical and emergency) of management alternatives;
- ✓ It is indispensable to design a strategy of drought impacts management that is dynamic enough to be capable of adapting to the severity of water shortages;
- ✓ It is crucial to consider and give high priority to all the alternative management options available, including those of non-supply nature (demand modification, impacts minimization).

## **Chapter 5: CONCLUSIONS AND RECOMMENDATIONS**

### **5.1. CONCLUSIONS**

Drought is a worldwide phenomenon that impacts industrialized and developing countries alike. Unfortunately, it is the developing countries that are least able to effectively respond to drought and the impacts can be very severe. In developed countries, like the USA, researchers and practitioners have developed different frameworks for planning the mitigation of drought impacts. Some of these frameworks have been suggested for use in developing countries; however, the adaptation of these frameworks to the conditions in the developing countries has been minimal.

The goal of this research was to integrate the best concepts of drought impact management from the developed countries into a framework that would be particularly suitable for use in developing countries. This framework would, by necessity, integrate the strategic, tactical and emergency responses. In developing countries, the lack of the strategic component has often kept the situation of drought impacts management from improving over time. The framework was developed using a suggested list of management options that should be valid in many developing countries. In the event that other options are needed, the framework is flexible enough to handle those changes.

An MCDA approach was used as the organizing concept to evaluate these management options given the management phase and the preferences of the decision makers. The MCDA approach was selected because it is easy to implement in a spreadsheet, it is very adaptable to different sets of options or criteria, and it is easy to assess the sensitivity of the outcomes with respect to changes in the relative importance of weights.

Two case studies demonstrated the potential applicability of the framework to different socio-economic contexts. The first case study was for the developing country of Mali in Africa. The study used data from the Niger River to demonstrate a process for analyzing streamflows to develop a sustainability index related to the average, maximum and minimum flows. This index was then used to guide the definition of the priority order of the management objectives for the MCDA analysis. The second case study was for a city in the USA. This case study demonstrated the general applicability of the framework and illustrated the differences in outcomes that might be expected when comparing applications from developed and developing countries. These case studies also demonstrated how sensitivity analysis of the MCDA model could be used to determine a set of robust results that might satisfy a majority of the stakeholders and give consistent management options over the various stages of a drought.

For the case study in Mali, the assessment of flow data considering different gaging stations showed that over the last three decades both the Niger River and the Bani River (its tributary) have consistently sustained large deficits in their flows. In both cases, the three flow thresholds of average, minimum and maximum flows have been affected to different extents. At all the selected gaging stations, the annual minimum flows seem to have sustained the most severe deficits, which makes them the least sustainable of the three flow types.

Although the long-term average values were used as thresholds in this research, they are for the most part much higher than the flows of the past three decades. Using these thresholds may have resulted in larger values of annual deficits, cumulative deficits and long run lengths, which made the analysis more conservative. For future analysis of the situation, it may be more appropriate to consider a change in the average values over the past three decades. This is especially true for the Bani River, which has seen its flows decrease exponentially; the decrease has caused the flows to be consistently below the long-term average values since the early 1970s.

In addition to the general decline in flows, the difference in intensity of the deficits affecting the three flow types suggests that factors other than deficits in rainfall may be involved. One of the potential factors affecting low flows may be a change in the recharge pattern of aquifers. Changes in land cover have a direct incidence on runoff coefficient, which, with sediment transport

are likely to affect the flows. Environmental degradation and subsequent erosion (The IUCN Sahel studies, 1991) are known to be a major problem in the whole Sahel region, which is expanding southward and includes a big part of the Niger River basin.

This research showed that for the gaging stations studied the Niger River is prone to have deficits every two years on average. The average run length of deficits sequences is two years for all flows types; the maximum run length ranging from 11 to 18 years. Except for the annual minimum flows, the run length of the deficits in the other flow types seems to increase slightly from south to north, which is consistent with the increased water losses in the inner delta from south to north.

Overall, the results have shown that using different thresholds may help provide more relevant information on drought impacts than a single threshold, such as mean annual flow. For the same period of deficits, the severity of the deficits may vary significantly from one flow type to another. This information may be useful when defining the priority order of the management objectives.

Based on the potential severity of deficits in the three flow types and other considerations, a priority order may be defined for the generic set of management objectives to which weights will be assigned accordingly.

To improve drought planning and implementation of “National action programs”, this research developed a spreadsheet MCDA model that can be used to design a dynamic operational strategy for drought impacts management. A generic set of the management options with potential to achieve the management objectives was identified. The model was applied to cases studies of drought impacts management in Mali and in the USA.

For the case study in Mali, the model was applied to a series of potential management actions, which for the most part have already been tried in previous efforts of drought mitigation. The results of the assessment showed, as anticipated, that the model worked well for identifying and ranking the most relevant management actions for different priority orders of the management objectives or drought severity levels. For the baseline conditions, the three priority orders and at each drought severity level, the model produced a unique ranking of the management options. From the normal conditions to the beginning of drought and to the crisis stage, changes observed in the ranking of the alternative options can help identify three main patterns:

- ✓ The management options moving up in the ranking are those becoming increasingly relevant to the tactical and emergency management. This is what the model was expected to do. Alternative 15 (Conditional reservoir operation), alternative 16 (Prioritizing water uses) and alternative 13 (application of pricing rate structure) and others fall into this category;

- ✓ The management options moving down in the ranking are those that have less direct impact in tactical and emergency management. This is also as expected. Alternative 21 (Drought early detection and warning), alternative 18 (New large storages) and others fall into this category;
- ✓ The management options, maintaining consistently their initial ranking or making small changes in either direction, are those insensitive to the severity levels of the drought.

The three patterns described above provide a basis for potentially defining a consistent operational strategy over all the drought stages and management objectives. The ranking of management options identified at each stage of a drought can then be analyzed in order to develop overall recommendations for the timing and sequencing of the implementation of the options over the different management phases.

Despite their extensive use for the management of drought impacts in the past, some of the alternative actions have shown by their ranking that they might not be the best choices in terms of relevance and sustainability.

Alternative 11 (water delivery by individual vendors) and alternative 8 (diesel powered new rural water distribution system) are among the management options, which appear to be implemented by decision makers' preference rather than based on actual performance.

Based on these results, the application of the model has produced an assessment consistent with the anticipated actual performance of the alternative options in the field. Therefore, the need for an effective management and optimal allocation of the resources call for the assessment framework in order to define the timing and sequencing of the management options most relevant to the management of drought impacts.

As described in detail in chapter 4, the model was also applied to the case study of a city in the USA in order to test its applicability to the situation of an industrialized society and identify any contrasts with the results of the first application. In terms of applicability, the results have shown that the model can perform well in the context of a developed country. Like the assessment in Mali, the results of this application produced similar patterns of changes in the ranking at different levels of drought severity:

- ✓ The alternative options with increasingly better ranking as the drought gets worse are alternative 4 (Regulatory measures), alternative 8 (Restrictions on water uses) and alternative 9 (Acquisition of additional supplies). However, it is important to note that in the overall analysis for all drought stages alternatives 8 and 9 are not ranked high enough to justify their selection as part of an overall strategy;
- ✓ The alternative options with decreasing relevance are alternative 3 (Incentive programs), alternative 5 (Operational measures) and alternative 6 (Raw water requirement). Except for alternative 3, the

low ranking of the two other options of this category makes them less relevant anyway.

- ✓ Alternative 7 (Storage capacity), alternative 1 (Educational programs) and alternative 2 (Rate structures) form the third category of options maintaining the same high position in the ranking for all levels of drought severity; by all accounts, they are relevant to all stages of management.

For this city the overall management strategy will consist of implementing alternative 7 in strategic terms, alternative 1 and 2 in strategic, tactical and emergency terms; the other options may be following priority order: alternatives 3, 4, 5, 6, 8 and 9. Again the model performed as expected and the results of the MCDA model were consistent with the decisions the City has previously made.

The results have also shown some contrasts between the situation in Mali and that of the City in the USA. The main differences include the fact that:

- ✓ Certain sub-criteria, such as "Potential poverty reduction" might not be relevant to developed countries where the access to water supply services seems not to have any bearing on the economic status;
- ✓ Due to the availability of financial resources and expertise in the City, the criteria of feasibility and sustainability and their sub-criteria are not a big issue, compared to the constraints they can be in poor countries;

- ✓ When the model is applied to a large area such as a basin or country like Mali, a generic set of management objectives is used. However, when the scale is smaller, such as the application to the City in the USA, then the set of management objectives will be limited. For example, the City application focused on the single objective of water supply.

## **5.2. CONTRIBUTIONS**

This research has produced a framework for drought impacts management that is specifically focused on the situation in developing countries.

Management options have been identified that are practical to use. New criteria and sub-criteria have been developed that are more relevant to the conditions of poor countries and reflect the integrated character of drought impacts management. In particular:

- ✓ The criterion of "Relevance to the management objective" is designed to assess the relevance of the alternatives options to the three potential stages of drought impacts management, which are strategic, tactical and emergency;
- ✓ The criterion "Impacts on the management objectives" is designed to assess the relevance of the alternative option to each of the management objectives.

A MCDA model was used to organize the evaluation of options; it is flexible and easy to use. By defining the timing and sequencing of alternative options, this study has achieved the objective of developing the framework

for the integration of the strategic, tactical and emergency management of drought impacts. The operational strategy is defined using the timing and sequencing identified by the model in order to ensure consistency in the policies of drought impacts management.

### **5.3. RECOMMENDATIONS**

The results of drought assessment have revealed the urgency to explore the causes of the consistent decline of the flows of the Niger River and its tributary of the Bani River; it appears that factors other than rainfall deficits may be at play. In the current situation, while there is a potential for all the flow types to sustain deficits, the annual minimum flows seem to be most at risk. Therefore, when dealing with the potential impacts of flow deficits, the management objectives relying on low flows need to be considered critical.

At its current state of development, the MCDA model has the potential for application to drought impacts management in any setting. However, for a successful application, the model may need to be refined in certain regards.

Among other things, the improvements may include:

- ✓ A design of the user interface, which could allow the user to input data and run the model without having to access the Excel worksheet for data entry;
- ✓ Enabling the model to be easily adaptable to varying numbers of potential alternative options, criteria and sub-criteria;

- ✓ Defining new criteria and sub-criteria or refining the existing ones in order to reflect the reality of the assessment need at hand;
- ✓ Having different players make the qualitative assessment of the potential management options in order to find the best compromise possible in case of discrepancies or ambiguities;
- ✓ The selection of the management options to be based on their performance in the assessment rather than on the simple preference as has been the routine until now.

Overall, there is urgency to extend current drought impacts management planning by adopting the framework of definition of the operational strategy as suggested by this study.

## References

- Abrams Len. (2000). Drought Policy-Water Issues. The African Water Page, <http://www.africanwaterpage.org>
- Balek Jaroslav. (1997). "Hydrology and water resources in tropical Africa." *Development in water science, 8*, Elsevier North-Holland, Inc., N.Y.
- Brooks N. (1999). Dust-climate interactions in the Sahel-Sahara zone. Ph. D. Thesis. University of East Anglia, UK.
- Cabrera E. and Garcia-Serra J. (1999). Drought management planning in water supply systems. *Proceedings from the UIMP international Course held in Valencia, December 1997*. Kluwer Academic Publishers, Dordrecht, TheNetherlands.
- Clarke J., and Noin D. (1998). "Population and Environment in Arid Regions." *Man and the Biosphere Series, Vol. 29*. UNESCO, Paris, and Parthenon Publishing Group Inc. One Blue Hill Plaza, Pearl River, New York.
- Colombo B., Demeny P., and Prutz M. F. (1996). Resources and Population: Natural, Instructional, and Demographic Dimensions of Development. *Oxford University Press, Oxford, UK*.
- Colorado Division of Disaster Emergency Services (1990). The Colorado Drought Response Plan. *The Office of the Governor, Denver, Colorado*.
- Colorado Division of Disaster Emergency Services (2001). The Colorado DroughtResponse Plan. *The Office of the Governor, Denver, Colorado*.
- Davy E.G., Mattei F. et Solomon S.I. (1976). "Special environmental Report No.9: An evaluation of climate and water resources for development in the Sudano-Sahelian zone of West Africa." *WHO-No. 459 Secretariat of the World Meteorological Organization*. Geneva, Switzerland.
- Direction Nationale de l'Hydraulique et de l'Energie (DNHE). (1990). "La Synthèse Mali Hydrogeologique du Mali." Bamako,

- Republique du Mali (in French).
- Direction Nationale de l'Hydraulique et de l'Energie (DNHE). (1990).  
"Le Schema Directeur de la Mise en Valeur des Ressources en Eau  
du Mali." Bamako, Republique du Mali (in French).
- Direction Nationale de l'Hydraulique (2000). "Rapport National  
sur la Formulation de la Vision de l'Eau à l'Horizon 2025"  
Bamako, Republique du Mali (in French).
- Faucheux S., and O'Connor M. (1998). Valuation for Sustainable  
Development: Methods and Policy Indicators. *Edward Elgar  
Publishing Limited*. Lansdown Place, Cheltenham, Glos. UK
- Food and Agriculture Organization-FAO (1997). "Irrigation potential in  
Africa: a basin approach",  
<http://www.fao.org/docrep/W4347E/w4347e00.htm>, 1997
- Fort Collins Utilities. (2002). Annual Operating Report
- Ganoulis J., Duckstein L., Litherathy P., and Bogardi I. (1996).  
"Transboundary Water Resources Management: Institutional and  
Engineering Approaches." *NATO ASI Series 2. Environment – Vol.  
7*. Springer-Verlag Berlin Heidelberg New York.
- Ganoulis J. (1991). "Water Resources Engineering Risk Assessment"  
NATO ASI Series, Series G: Ecological Sciences, Vol. 29. Springer-  
Verlag Berlin Heidelberg New York.
- Glantz M. H. (1987). Drought and hunger in Africa: denying famine a  
future. *The Press Syndicate of the University of Cambridge*, the  
Pitt Building, Trumpington Street, Cambridge, New York, NY.
- Godana B. A. (1985). Africa Shared Water Resources: Legal and  
Institutional Aspects of the Nile, Niger and Senegal River  
Systems. *Lynne Rienner Publishers, Inc.*, Boulder, Colorado.
- Goodness G. M., Palutikof J. P., and Davies T. D. (1992). The nature  
and causes of climate change: Assessing the long-term future.  
*Studies in climatology series*. Lewis Publishers, Boca Raton,  
Florida.
- Gordon J. Y., Dooge J. C.I., and Rodda J.C. (1994) Global water

- Resources issues. *Cambridge University Press*, New York, NY.
- Grigg N. S. and Vlachos E. C. (1990) "Drought water Management." *Proceedings of a National workshop in Washington, D.C. (November 1-2, 1988)*. International School for Water Resources, Colorado State University.
- Grigg N. S. (1996). *Water Resources Management: Principles, Regulations and cases. McGraw-Hill Companies, Inc.* New York.
- Gritzner J. A. (1988). "The West African Sahel: Human Agency and Environmental Change." Research paper/University of Chicago, The Committee on Geographical studies; 226.
- Hafkamp W. A. (1984). "Economic-environmental modeling in a national-regional System." *Studies in regional science and urban economics*, 10. Elsevier Science publishers B.V. Amsterdam, The Netherlands.
- Haimes Y. Y. and Allee D. J. (1984). *Multiobjective Analysis in Water Resources. American Society of Civil Engineers.* New York, N. Y.
- Hayes, Michael J. (1999). "Drought Indices," <http://enso.unl.edu/ndmc/enigma/indices>, National Drought Mitigation Center.
- Kaczmarek Z., Strzepek K. M., Somlyody L., and Priazhinskaya V. (1996). "Water resources management in the face of climatic/hydrologic uncertainties." *Water Science and technology Library, Vol. 18.* Kluwer Academic Publishers, Dordrecht, the Netherland.
- Karavatis C. A. (1992). "Drought Management Strategies for Urban Water Supplies: The case of Metropolitan Athens." Ph. D. Dissertation, Colorado State University, Colorado.
- Karpe H. J., Otten D., and Trinidate S. C. (1990). *Climate and development: Climate change and variability and the resulting social, economic and technological implications. Springer-Verlag Berlin.* Heidelberg New York.
- Kindler J., Russel C. S., Bower B. T., Gouevsky, I., Maidment D. R.,

- and Sewell W. R. D. (1984). Modeling water demands. Academic Press Inc. Orlando, Florida.
- Lakh Mamadou, (1998). "Organisation pour la Mise en Valeur du Fleuve Senegal." Conférence Internationale "Eau et Développement Durable," Paris, <http://www.oieau.fr/ciedd/fra/frames/index.htm> (in French).
- Lemons J. and Brown D. A. Sustainable Development: Science, ethics, and public policy. Environmental science and technology library, Vol. 3. Kluwer Academic Publishers, Dordrecht, the Netherland.
- Loucks D. P., Stedinger J. R., and Haith D. A. (1981). Water resource systems planning and analysis. *Prentice-Hall, Inc.* Englewood Cliffs, N.J.
- McCuen R.H. (1998). Hydrologic Analysis and Design, 2<sup>nd</sup> edition. Prentice Hall
- Mortimore M. (1989). Adapting to drought: Farmers, famines and desertification in West Africa. *Cambridge University Press*, Cambridge, New York.
- Newman J. L. (1975). Drought, Famine and Population Movements in Africa. *Publishing Desk*, Syracuse University, Syracuse, New York.
- Perritt R. W. and Masucci M. (1997). "Managing the Effects of Recent Droughts in the Southern United States." *Human & Environmental Interchange.*" Harcourt Brace & Company.
- Porter R. C., Boakye-Yiadom L. Jr., Mafusire A., and Tsheko B. O. The Economics of water and waste in three African capitals. *Ashgate Publishing Limited.* Hants, England.
- Rangeley, R., Thiam, B. M. Andersen, R. A. and Lyle, C. A. 1994. "International River Basin Organizations in Sub-Saharan Africa." *World Bank Technical Paper Number 250, Africa Technical Department Series.* The World Bank, Washington, D.C.
- Riebsame W. E., Changnon S. A. Jr., and Karl T. R. (1991). Drought

- and natural resources management in the United States (Impacts and implications of the 1987-89). *Westview Special Studies in Natural Resources and Energy Management*. Westview Press, Inc., Boulder, Colorado.
- Roder W. (1994). Human adjustment to Kainji reservoir in Nigeria. *University Press of America, Inc.* Lanham, Maryland.
- Rodier J. (1964). Regimes hydrologiques de l'Afrique noire à l'ouest du Congo, *ORSTOM*. Paris.
- Rosbjerg D., Boutayeb N. E., Gustard A., Kundzewicz and Rasmussen P. F. (1997). "Sustainability of Water Resources under increasing Uncertainty." *International association of hydrological sciences*. Publication n # 240. IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, UK.
- Salas D. J., Smith R. A. and Tabio III G. Q. and Haeng. H. J. (1995). Statistical computer techniques in water resources and environmental engineering, (Chapters 1 through 8);
- Salas J. D., Delleur J. W., Yevjevich V. and Lane W. L. (1997). Applied Modeling of Hydrologic Time Series (Fourth Printing). Water Resources Publications, LLC, Littleton, Colorado 80161, USA;
- Sanders J. H., Shapiro B. I., and Ramaswamy S. (1996). *The Johns Hopkins University Press*, Baltimore, MD.
- Secretariat Permanent du PNAE-CID (1998). Résumé du PNAE/PAN-CID. Ministère de l'Environnement du Mali, Bamako.
- Servat E., Hughes D., Fristsch J. M., and Hulme M. (1998). "Water Resources variability in Africa during the XXth century (Variabilité des ressources en eau en Afrique au XXème Siècle)." *International association of hydrological sciences*. Publication n° 252. IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, UK.
- Sharma N. P., Damhaug T., Gilgan-Hunt E., Grey D., Okaru V., and Rothberg D. (1996). "African Water Resources." *World Bank Technical Paper No.331*. Africa Technical Department Series. The

- World Bank, Washington, D.C.
- Simonovic S. P., Kundzewicz Z., Rosbjerg D., and Takeuchi K. (1995). "Modelling and Management of Sustainable Basin-scale Water Resources Systems." *International association of hydrological sciences*. Publication n° 231. IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, UK.
- Sircouloulon J., Lebel and Arnell N. W. (1999). "Assessment of the impacts of Climate variability and change on the hydrology of Africa" in Dan J. C. V. (1999). "Impacts of Climate Change and climate variability on hydrological regime." *Cambridge University Press*, Cambridge, New York.
- Smith J.B., Bhatti N., Menzhulin G., Benioff R., Budyko M. I., Campos M. Jallow B., Rijsberman F. (1996). Adapting to climate change: Assessment and issues. *Springer-Verlag New York Inc.*, New York, NY.
- Somerville C. M. (1986). Drought and aid in the Sahel (A decade of Development cooperation). Westview Press, Inc., Boulder, Colorado.
- Taku T. A. (1999). Framework for industrialization in Africa. *Praeger Publishers*, Westport, CT.
- Tannehil I. R. (1947). Drought; Its causes and effects. Princeton University Press, Princeton, N.J.
- Task Committee on Sustainability Criteria, Water Resources Planning And Management Division, ASCE and Working Group, UNESCO/IHP IV Project M-4.3 (1998). "Sustainability criteria for water resource systems." *ASCE*, Reston, Virginia.
- The National Research Council. (1991). Toward Sustainability: A Plan For Collaborative Research on Agriculture and Natural Resource Management. *National Academic Press*. Washington, D.C.
- The World Bank (1985). "Desertification in the Sahelian and Sudanian zones of West Africa." The International Bank for Reconstruction and Development/The World Bank, Washington, D.C.
- Traore Z. N. (1998). Low flow frequency analysis of the Niger River in its Inland Delta reach, Mali West Africa (Unpublished).

- Wilhite D. (1997) "Improving drought management in the West: The role of Mitigation and Preparedness" National Drought Mitigation Center, University of Nebraska.
- Wilhite D. A. (2000). Drought: a global assessment, Vol. 1. Routledge, New York.
- Wilhite D. A. (2000). Drought: a global assessment, Vol. 2. Routledge, New York.
- Wood A. P. and Ryden P. (1992). The IUCN Sahel Studies 1991. *IUCN, Gland, Switzerland and Cambridge, UK.*
- Yevjevich V., Hall W. A., and Salas J. D. (1978). Drought Research Needs. *Proceedings of the Conference on Drought Research Needs, held at Colorado State University, USA City, Colorado (December 12 15, 1977).* Water Resources Publications, USA City, Colorado.
- Young G. J., Dooge J. C. I., and Rodda J. R. (1994). Global water Resources issues. The Press Syndicate of the University of Cambridge, the Pitt Building, Trumpington Street, Cambridge, New York, NY.
- Zeleny M. (1982). Multiple Criteria Decision Making (*McGraw-Hill Series in Quantitative Methods for Management*). McGraw-Hill, Inc.

## **APPENDIX**

### **OVERVIEW OF WATER RESOURCES IN MALI**

## **1. INTRODUCTION**

Mali is a landlocked country located in the Sahel region of West Africa. It has a total surface area of 1,240,000 km<sup>2</sup> stretching between the latitudes north of 10° 30' and 25° 30', and from the longitudes 12° 00' (West) to 4° 00' (East). Due to this geographical situation, the country has a tropical climate, which is characterized by two alternating dry and rainy seasons.

The Niger and Senegal rivers are the main perennial watercourses, which originate in Guinea and drain water from different countries of the region, including Mali.

### **1.1. Climate**

The climate of Mali is derived from the West African regional climate, which results from the interaction between westward air masses from the Sahara desert and northward humid cross-equatorial monsoons from the Gulf of Guinea (Rasmusson E. M., 1987). This interaction, in turn, is said to be the regional component of the tropical atmospheric circulation, which is taking place on a global scale. The location of the interaction between the two air masses mentioned above, known as the Intertropical Convergence Zone (ITCZ), is oscillating year-round in the north south direction, and determines the local rainfall regime. Unlike the year-round oscillations of the ITCZ over the equator in Central and East Africa, the migrations of the ITCZ in West

Africa are exclusively limited to the area north of the equator. As a result, West Africa has a tropical climate consisting of two alternating dry and rainy seasons. In terms of rainfall, the total annual volume varies significantly from the southern region to the Sahara desert in the north where it is not rare to see a whole year without rain.

## 1.2. Temperature, Relative humidity, and Evapotranspiration

At the stations representing the different climatic zones, the values of monthly mean temperature show little variation around the year (Synthese hydrologique du Mali, DNHE, 1990); the difference in annual mean temperatures is about a 2°C difference between Sikasso and Kidal.

Station	Jan	Feb	Marc	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year Mean
<b>Kidal</b>	20.3	23.4	27.0	30.8	33.7	34.7	33.0	31.5	32.1	30.2	25.6	21.4	28.6
<b>Nioro</b>	22.7	25.7	28.8	31.9	34.3	32.8	29.0	27.3	28.2	29.4	27.2	22.9	28.4
<b>Segou</b>	23.9	27.0	29.7	31.8	32.3	30.1	27.3	26.2	26.6	27.8	26.8	24.0	27.8
<b>Sikasso</b>	23.9	27.2	29.5	30.4	29.5	27.5	25.9	25.3	25.7	26.9	26.0	23.7	26.8

Table A-1.2-1: Average monthly temperatures (°c) at stations in different climatic zones

(Source: Synthese hydrologique du Mali, DNHE, 1990)

Except in the more humid southern zone where the average annual relative humidity may be above the threshold of 50%, the rest of the country exhibits much lower values.

Station	Jan	Feb	Marc	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year Mean
<b>Nioro</b>	27	23	22	22	29	45	65	75	70	50	34	30	41
<b>Sikasso</b>	34	31	37	49	61	70	77	82	78	71	57	47	58

Table A-1.2-2: Relative humidity average monthly values (%)

(Source: Synthèse hydrologique du Mali, DNHE, 1990)

The high evapotranspiration (table 3.1.2-3) certainly results from the combined condition of high temperatures and reduced relative humidity.

Station	Jan	Feb	Marc	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year Total
<b>Gao</b>	171	187	242	260	276	247	244	213	206	189	171	158	2564
<b>Bamako</b>	168	176	209	202	203	176	152	145	150	150	155	159	2045
<b>Sikasso</b>	112	126	149	157	161	136	129	126	124	129	116	108	1573

Table A-1.2-3: Average monthly values (mm) of evaporation and evapotranspiration

(Source: "Synthèse hydrologique du Mali, DNHE 1990 after Direction Nationale de Meteorologie")

### 1.3. Rainfall and water resources

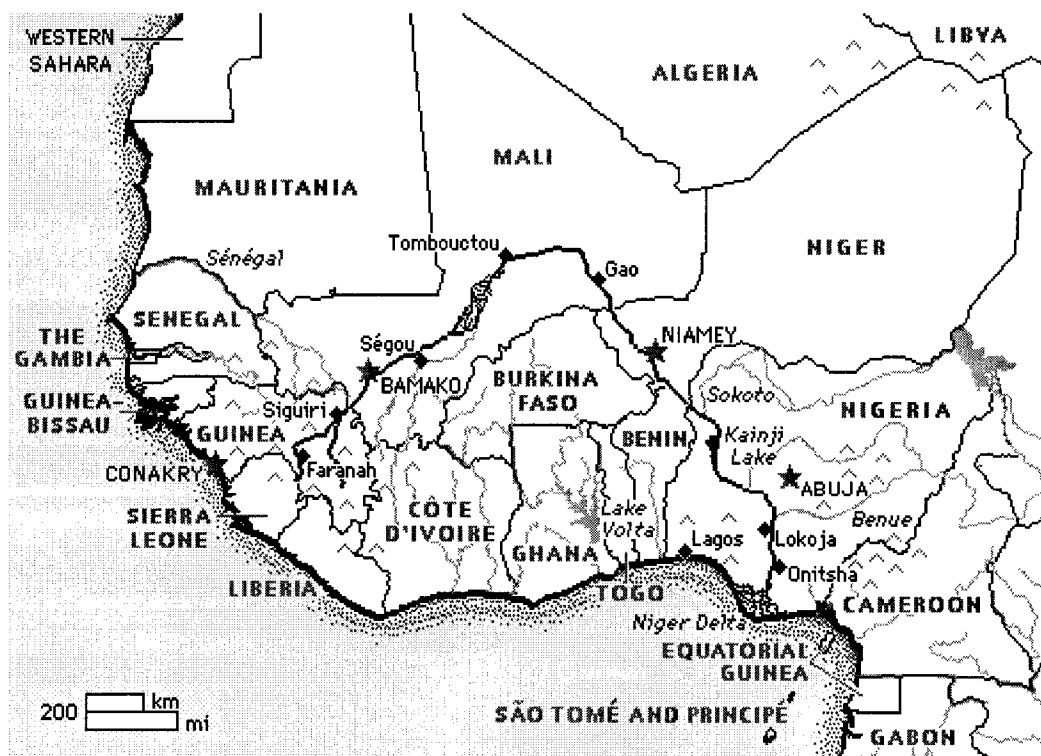
As mentioned before, the year-round migrations of the ITCZ determine the rainfall regime. Depending on the location, the rainy season may last three to seven months; the number of rainy days varies from 21 at Kidal to 98 Sikasso, and the total annual rainfall goes from 1288 in Sikasso to 137 mm in Kidal (Synthèse hydrologique du Mali, DNHE 1990.)

Station	Jan	Feb	Marc	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	An. Mean	Rainy Days
<b>Kidal</b>	0	0	0	1	7	10	35	56	25	3	0	0	137	21
<b>Nioro</b>	0	1	0	5	17	65	58	215	118	24	2	1	506	48
<b>Segou</b>	0	0	3	11	26	91	180	245	127	26	3	1	713	64
<b>Bamako</b>	1	0	4	17	65	141	204	333	213	66	7	1	1052	83
<b>Sikasso</b>	1	5	17	50	114	157	270	333	230	91	17	3	1288	98

Table A-1.3-1: Rainfall average monthly values (mm)

(Source: Synthèse hydrologique du Mali, DNHE 1990)

The entire surface area of Mali falls into the basins of the Senegal and Niger Rivers. Depending on the source and purpose, estimates of renewable water resources available to Mali in these two basins vary between 71 km<sup>3</sup>/year (DNH, 2000) and 100 km<sup>3</sup>/year (FAO, 1997) for an average year. In dry (1984) and wet (1967) years, these estimates are 40 km<sup>3</sup> and 87 km<sup>3</sup> respectively.



## **2. FLOWS CHARACTERISTICS**

### **2.1. The Niger River at Koulikoro gaging station**

At this gaging station, the Niger River has the average values of 65.13 m<sup>3</sup>/s for the minimum flows, 1384.85 m<sup>3</sup>/s for the annual mean flows, and 4926.93 m<sup>3</sup>/s for the annual maximum flows. The annual minimum flows, compared to the other two types, have a higher coefficient of variation; they are followed by the annual mean flows. Figure 2.1-1 shows the graphs of the different flows.

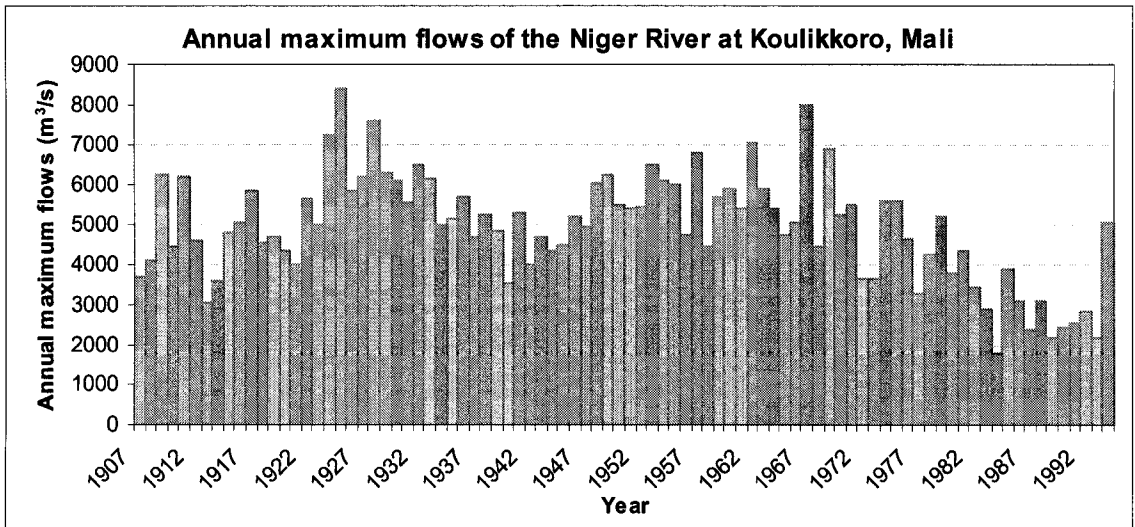
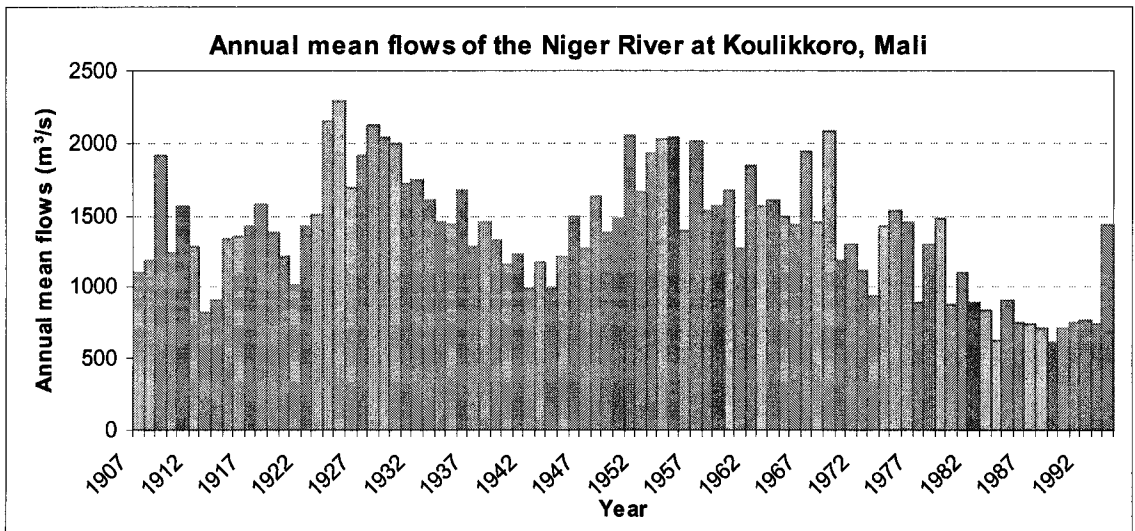
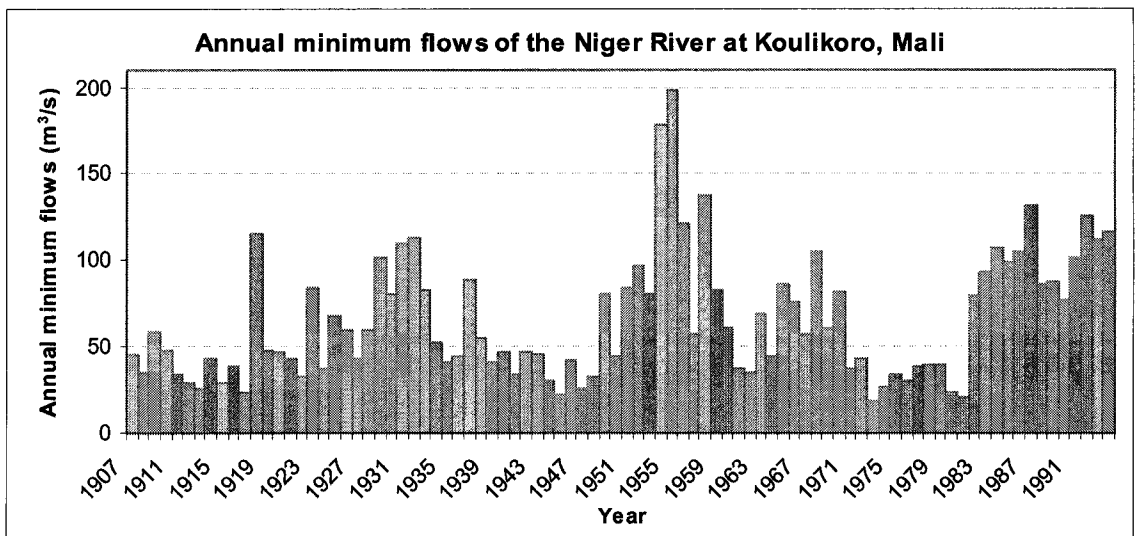


Figure A-2.1-1: Flows of the Niger River at Koulikoro, Mali

### 2.1.1. Annual flows: statistics and distribution

The fluctuation of the flow volume between flood flows (average 4926.93 m<sup>3</sup>/s) and low flows (with average of 65.13 m<sup>3</sup>/s) is consistent with a very high seasonal variability the flow regime of the Niger River.

Statistics	Types of annual discharge		
	Minimum	Average	Maximum
Mean	65.13	1384.85	4926.93
Standard Error	3.85	43.39	143.37
Median	53.55	1420.53	5015
Standard Deviation	36.09	407.01	1344.92
Sample Variance	1302.40	165659.50	1808816.91
Kurtosis	1.55	-0.62	-0.01
Skewness	1.17	0.08	-0.08
Coefficient of Variation	0.55	0.29	0.27
Range	179.8	1674.82	6620
Minimum	18.2	621.33	1800
Maximum	198	2296.15	8420

Table A-2.1.1-1: Statistics of the annual flows of the Niger River at Koulikoro, Mali

The normal probability distribution was fitted to the annual mean and maximum flows. The probability density function of the normal distribution is formulated as:

$$f(X) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left(\frac{X-\mu}{\sigma}\right)^2} \quad (\text{Equation 2.1.1-1})$$

Where:

- ✓  $\sigma$  is the standard deviation of the variable
- ✓  $\mu$  is the mean of the variable

The moment estimators of these parameters for the annual mean discharges are:

$$\checkmark \hat{\mu} = \frac{1}{N} \sum_{i=1}^N X_i ;$$

$$\checkmark \hat{\sigma} = \left[ \frac{1}{N} \sum_{i=1}^N (X_i - \mu)^2 \right]^{\frac{1}{2}} ;$$

The cumulative distribution function is formulated as:

$$F(X) = \int_{-\infty}^X f(X) dX = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^X e^{-\frac{1}{2}\left(\frac{X-\mu}{\sigma}\right)^2} dX \quad (\text{Equation 2.1.1-2})$$

$$F(u) = \Phi(u) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^X e^{-\frac{u^2}{2}} du \quad (\text{Equation 2.1.1-3})$$

Where  $u = \frac{X-\mu}{\sigma}$  and  $\Phi(\cdot)$  is the CDF of the standard normal distribution.

The skewness of the distribution of the annual minimum flows seems to be driven by the largest extreme values, especially those of 1954 and 1955; the gamma and lognormal distribution functions were both found to be good fit to annual minimum flows. For the gamma function, the moment estimators of the parameters are:  $\hat{\alpha} = 3.26$  and  $\hat{\beta} = 20.0$ . The normal probability distribution function was fitted to the both the annual mean and maximum flows. The histograms of the different flows and the results of probability functions fitting are shown in Figures A-2.1.1-1, Table A-2.1.1-1 and Figure A-2.1.1-2.

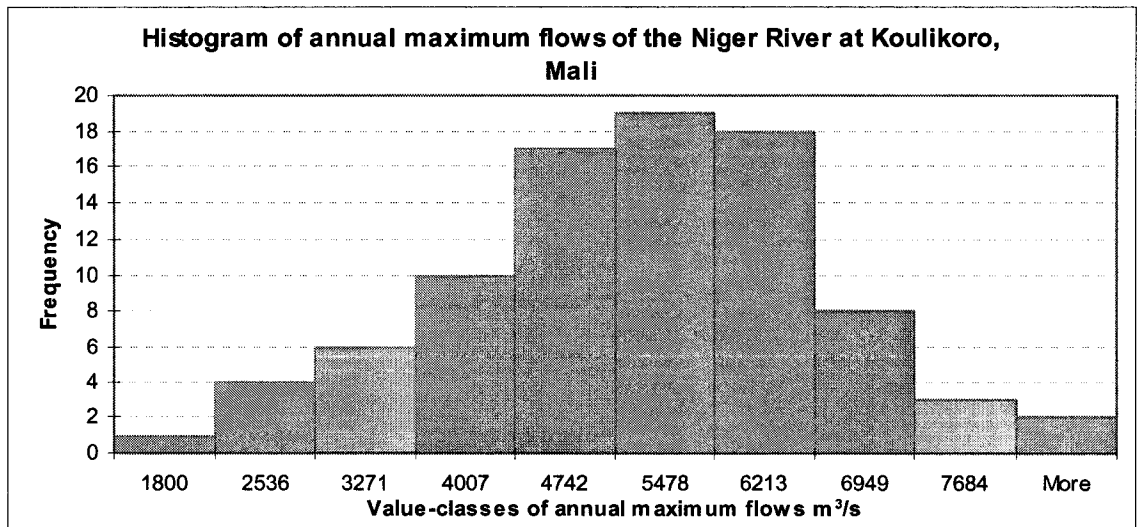
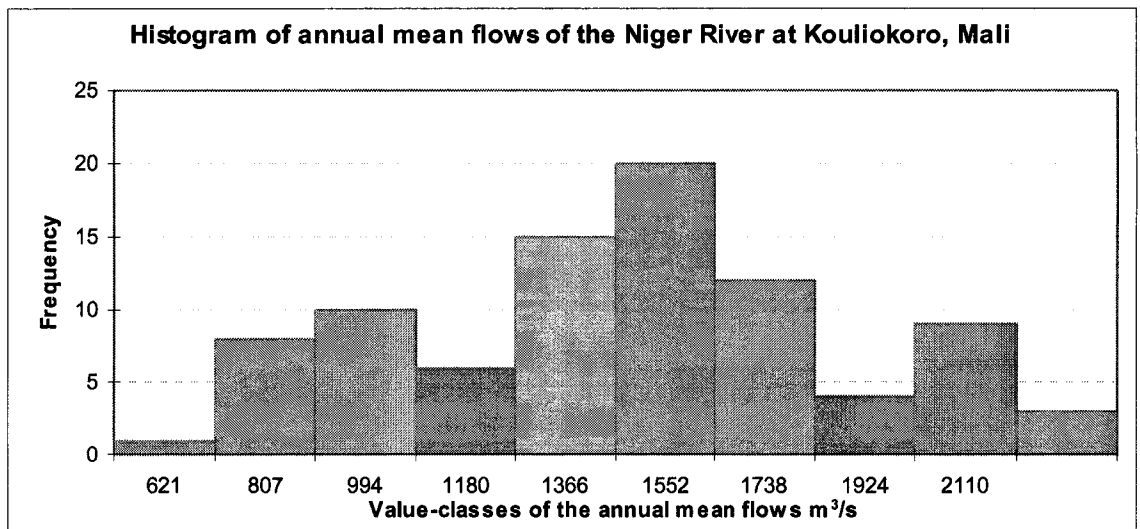
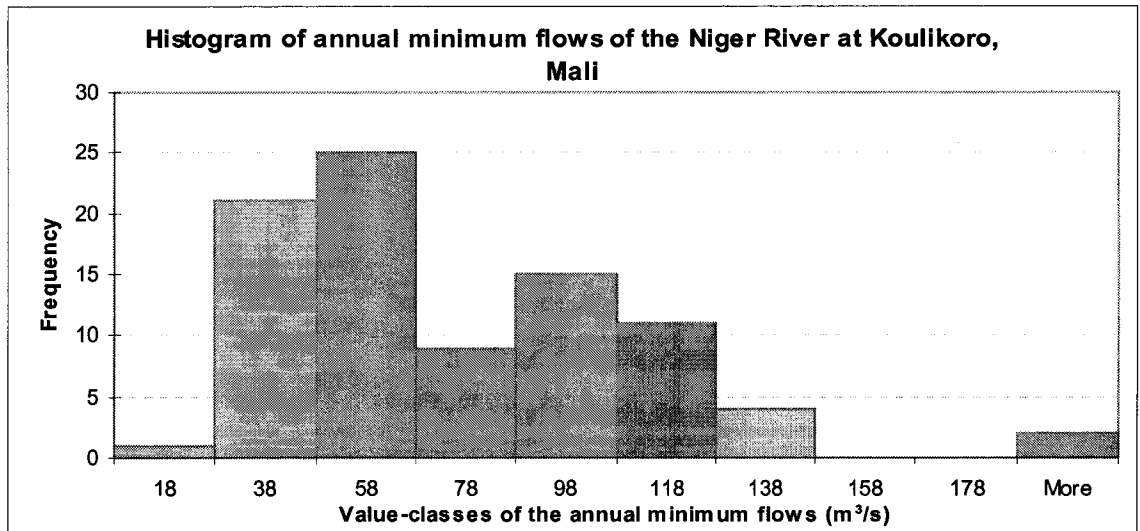


Figure 2.1.1-1: Histograms of the annual flows of the Niger River at Koulikoro Mali

Order	Annual Discharge (m <sup>3</sup> /s)			Return Period (Year)			Non-Exceedance probability distributions						
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of			CDF of Fitted Distribution			
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum Flows		Annual Mean flows: Normal	Annual Maximum flows: Normal
										Gamma	Lognormal		
1	18.2	621.33	1800	1.01	1.01	1.01	0.01	0.01	0.011	0.04	0.02	0.03	0.010
2	20.6	633.42	2190	1.02	1.02	1.02	0.02	0.02	0.022	0.06	0.03	0.03	0.021
3	22.6	713.49	2210	1.03	1.03	1.03	0.03	0.03	0.034	0.08	0.04	0.05	0.022
4	23	714.15	2390	1.05	1.05	1.05	0.04	0.04	0.045	0.08	0.05	0.05	0.030
5	23.1	733.67	2460	1.06	1.06	1.06	0.06	0.06	0.056	0.08	0.05	0.05	0.033
6	25.7	734.25	2540	1.07	1.07	1.07	0.07	0.07	0.067	0.10	0.07	0.05	0.038
7	25.9	748.50	2870	1.09	1.09	1.09	0.08	0.08	0.079	0.11	0.07	0.06	0.063
8	26.3	757.33	2920	1.10	1.10	1.10	0.09	0.09	0.090	0.11	0.08	0.06	0.068
9	28.7	767.25	3050	1.11	1.11	1.11	0.10	0.10	0.101	0.13	0.10	0.06	0.081
10	29.5	821.13	3100	1.13	1.13	1.13	0.11	0.11	0.112	0.14	0.11	0.08	0.087
11	29.9	837.23	3120	1.14	1.14	1.14	0.12	0.12	0.124	0.15	0.12	0.09	0.090
12	30	876.18	3280	1.16	1.16	1.16	0.13	0.13	0.135	0.15	0.12	0.11	0.110
13	32.8	887.99	3440	1.17	1.17	1.17	0.15	0.15	0.146	0.18	0.16	0.11	0.134
14	33	899.70	3560	1.19	1.19	1.19	0.16	0.16	0.157	0.18	0.16	0.12	0.155
15	33.3	910.55	3600	1.20	1.20	1.20	0.17	0.17	0.169	0.19	0.16	0.12	0.162
16	33.4	910.61	3630	1.22	1.22	1.22	0.18	0.18	0.180	0.19	0.17	0.12	0.167
17	34.1	929.60	3670	1.24	1.24	1.24	0.19	0.19	0.191	0.19	0.17	0.13	0.175
18	34.7	988.02	3710	1.25	1.25	1.25	0.20	0.20	0.202	0.20	0.18	0.16	0.183
19	34.7	991.77	3820	1.25	1.27	1.27	0.20	0.21	0.213	0.20	0.18	0.17	0.205
20	37.2	1020.54	3920	1.29	1.29	1.29	0.22	0.22	0.225	0.23	0.22	0.19	0.227
21	37.3	1101.28	3980	1.31	1.31	1.31	0.24	0.24	0.236	0.23	0.22	0.24	0.241
22	37.4	1107.76	4020	1.33	1.33	1.33	0.25	0.25	0.247	0.23	0.22	0.25	0.250
23	38.4	1121.43	4080	1.35	1.35	1.35	0.26	0.26	0.258	0.25	0.24	0.26	0.264
24	38.8	1158.73	4230	1.37	1.37	1.37	0.27	0.27	0.270	0.25	0.24	0.29	0.302
25	39.9	1171.96	4340	1.39	1.39	1.39	0.28	0.28	0.281	0.27	0.26	0.30	0.331
26	40.1	1190.57	4350	1.41	1.41	1.41	0.29	0.29	0.292	0.27	0.26	0.32	0.334
27	40.5	1191.83	4360	1.44	1.44	1.44	0.30	0.30	0.303	0.27	0.27	0.32	0.337
28	40.9	1211.98	4440	1.46	1.46	1.46	0.31	0.31	0.315	0.28	0.27	0.34	0.359
29	41.9	1216.38	4450	1.48	1.48	1.48	0.33	0.33	0.326	0.29	0.29	0.34	0.361
30	42.8	1223.33	4460	1.51	1.51	1.51	0.34	0.34	0.337	0.30	0.30	0.35	0.364
31	43	1244.43	4500	1.53	1.53	1.53	0.35	0.35	0.348	0.31	0.31	0.37	0.375
32	43.3	1265.33	4540	1.56	1.56	1.56	0.36	0.36	0.360	0.31	0.31	0.38	0.387
33	43.4	1268.63	4620	1.59	1.59	1.59	0.37	0.37	0.371	0.31	0.31	0.39	0.410
34	44.6	1279.18	4640	1.62	1.62	1.62	0.38	0.38	0.382	0.33	0.33	0.40	0.416
35	44.6	1282.30	4680	1.62	1.65	1.65	0.38	0.39	0.393	0.33	0.33	0.40	0.427
36	44.7	1297.53	4680	1.68	1.68	1.65	0.40	0.40	0.393	0.33	0.33	0.42	0.427
37	45	1304.17	4700	1.71	1.71	1.71	0.42	0.42	0.416	0.33	0.34	0.42	0.433
38	45.3	1333.58	4740	1.75	1.75	1.75	0.43	0.43	0.427	0.33	0.34	0.45	0.445
39	46.1	1339.78	4770	1.78	1.78	1.78	0.44	0.44	0.438	0.34	0.35	0.46	0.454
40	46.7	1361.35	4790	1.82	1.82	1.82	0.45	0.45	0.449	0.35	0.36	0.48	0.459
41	47.1	1382.61	4850	1.85	1.85	1.85	0.46	0.46	0.461	0.36	0.37	0.50	0.477
42	47.7	1383.82	4940	1.89	1.89	1.89	0.47	0.47	0.472	0.37	0.38	0.50	0.504
43	47.9	1390.83	4980	1.93	1.93	1.93	0.48	0.48	0.483	0.37	0.38	0.51	0.516
44	52.1	1420.03	4990	1.98	1.98	1.98	0.49	0.49	0.494	0.42	0.44	0.53	0.519

Table A-2.1.1-2: Probability distributions of the flows of the Niger River at Koulikoro, Mali

Order	Annual Discharge (m <sup>3</sup> /s)			Return Period (Year)			Non-Exceedance probability distributions						
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of			CDF of Fitted Distribution			
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum Flows		Annual Mean flows: Normal	Annual Maximum flows: Normal
										Gamma	Lognormal		
45	55	1421.03	5040	2.02	2.02	2.02	0.51	0.51	0.506	0.46	0.48	0.54	0.533
46	56.9	1428.37	5060	2.07	2.07	2.07	0.52	0.52	0.517	0.48	0.51	0.54	0.539
47	57.2	1435.03	5060	2.12	2.12	2.07	0.53	0.53	0.517	0.48	0.51	0.55	0.539
48	58.6	1435.75	5160	2.17	2.17	2.17	0.54	0.54	0.539	0.50	0.53	0.55	0.569
49	59.4	1436.70	5210	2.23	2.23	2.23	0.55	0.55	0.551	0.51	0.54	0.55	0.583
50	59.6	1448.39	5210	2.28	2.28	2.23	0.56	0.56	0.551	0.51	0.54	0.56	0.583
51	60.8	1450.67	5240	2.34	2.34	2.34	0.57	0.57	0.573	0.53	0.55	0.56	0.592
52	60.9	1452.00	5260	2.41	2.41	2.41	0.58	0.58	0.584	0.53	0.56	0.57	0.598
53	67.8	1454.18	5320	2.47	2.47	2.47	0.60	0.60	0.596	0.60	0.63	0.57	0.615
54	69.4	1475.31	5380	2.54	2.54	2.54	0.61	0.61	0.607	0.62	0.65	0.59	0.632
55	75.5	1480.79	5380	2.62	2.62	2.54	0.62	0.62	0.607	0.68	0.71	0.59	0.632
56	77.4	1492.21	5400	2.70	2.70	2.70	0.63	0.63	0.629	0.69	0.72	0.60	0.637
57	79.1	1492.73	5470	2.78	2.78	2.78	0.64	0.64	0.640	0.71	0.73	0.60	0.657
58	80.1	1514.83	5500	2.87	2.87	2.87	0.65	0.65	0.652	0.72	0.74	0.63	0.665
59	80.1	1534.37	5500	2.87	2.97	2.87	0.65	0.66	0.652	0.72	0.74	0.64	0.665
60	80.5	1540.17	5530	3.07	3.07	3.07	0.67	0.67	0.674	0.72	0.74	0.65	0.673
61	81.2	1558.82	5600	3.18	3.18	3.18	0.69	0.69	0.685	0.72	0.75	0.67	0.692
62	83	1563.45	5620	3.30	3.30	3.30	0.70	0.70	0.697	0.74	0.76	0.67	0.697
63	83.2	1564.23	5660	3.42	3.42	3.42	0.71	0.71	0.708	0.74	0.76	0.67	0.707
64	83.9	1573.92	5680	3.56	3.56	3.56	0.72	0.72	0.719	0.75	0.77	0.68	0.712
65	84.1	1605.08	5720	3.71	3.71	3.71	0.73	0.73	0.730	0.75	0.77	0.71	0.722
66	86.8	1610.70	5870	3.87	3.87	3.87	0.74	0.74	0.742	0.77	0.79	0.71	0.758
67	86.9	1628.17	5870	4.05	4.05	3.87	0.75	0.75	0.742	0.77	0.79	0.73	0.758
68	88	1655.11	5910	4.24	4.24	4.24	0.76	0.76	0.764	0.77	0.79	0.75	0.768
69	89	1674.61	5910	4.45	4.45	4.24	0.78	0.78	0.764	0.78	0.80	0.76	0.768
70	93.8	1680.88	6020	4.68	4.68	4.68	0.79	0.79	0.787	0.81	0.83	0.77	0.792
71	96.3	1690.78	6060	4.94	4.94	4.94	0.80	0.80	0.798	0.82	0.84	0.77	0.800
72	99.7	1714.92	6080	5.24	5.24	5.24	0.81	0.81	0.809	0.84	0.85	0.79	0.804
73	101	1749.67	6090	5.56	5.56	5.56	0.82	0.82	0.820	0.85	0.86	0.81	0.806
74	102	1848.73	6140	5.93	5.93	5.93	0.83	0.83	0.831	0.85	0.86	0.87	0.816
75	105	1909.23	6190	6.36	6.36	6.36	0.84	0.84	0.843	0.87	0.88	0.90	0.826
76	105	1913.97	6220	6.36	6.85	6.85	0.84	0.85	0.854	0.87	0.88	0.90	0.832
77	107	1931.88	6240	7.42	7.42	7.42	0.87	0.87	0.865	0.88	0.88	0.91	0.836
78	110	1943.77	6240	8.09	8.09	7.42	0.88	0.88	0.865	0.89	0.89	0.92	0.836
79	112	1993.86	6290	8.90	8.90	8.90	0.89	0.89	0.888	0.89	0.90	0.93	0.845
80	113	2014.31	6500	9.89	9.89	9.89	0.90	0.90	0.899	0.90	0.90	0.94	0.879
81	115	2024.42	6520	11.13	11.13	11.13	0.91	0.91	0.910	0.90	0.91	0.94	0.882
82	117	2035.58	6800	12.71	12.71	12.71	0.92	0.92	0.921	0.91	0.91	0.95	0.918
83	121	2040.33	6910	14.83	14.83	14.83	0.93	0.93	0.933	0.92	0.92	0.95	0.930
84	126	2051.99	7050	17.80	17.80	17.80	0.94	0.94	0.944	0.93	0.93	0.95	0.943
85	132	2083.38	7250	22.25	22.25	22.25	0.96	0.96	0.955	0.95	0.94	0.96	0.958
86	138	2118.97	7580	29.67	29.67	29.67	0.97	0.97	0.966	0.96	0.95	0.96	0.976
87	179	2152.28	8000	44.50	44.50	44.50	0.98	0.98	0.978	0.99	0.98	0.97	0.989
88	198	2296.15	8420	89.00	89	89.00	0.99	0.99	0.989	1.00	0.99	0.99	0.995
Coefficient of determination R <sup>2</sup> =										0.97	0.97	0.99	0.99

Table A-2.1.1-2: Probability distributions of the flows of the Niger River at Koulikoro, Mali

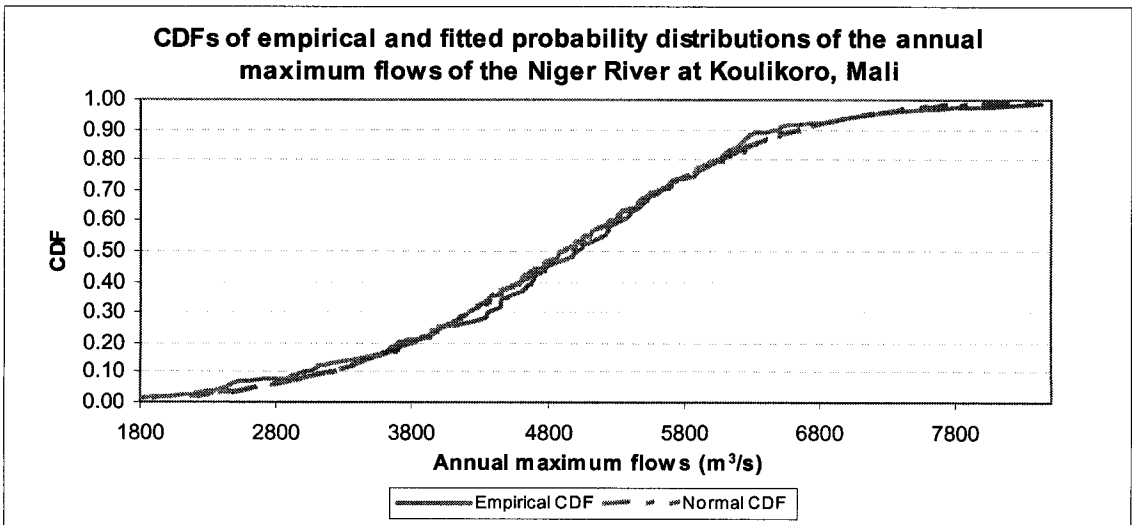
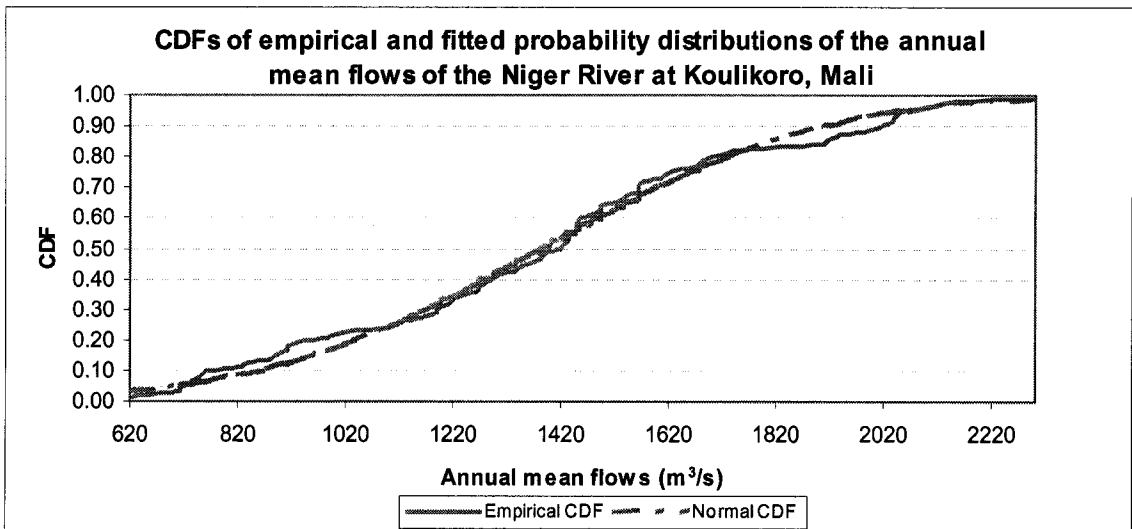
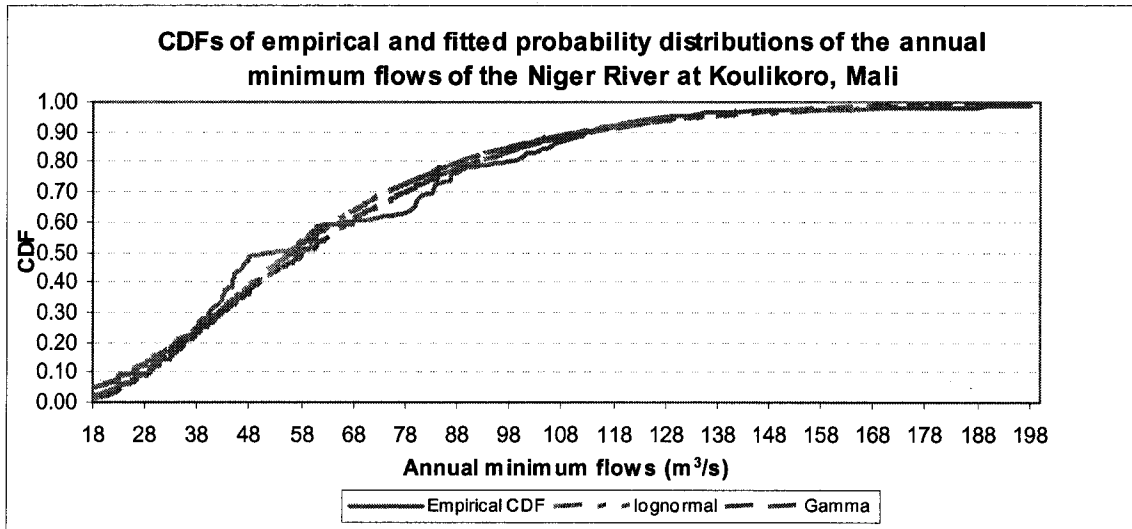


Figure A-2.1.1-2: CDFs of probability distributions of the flows of the Niger River at Koulikoro, Mali

### 2.1.2. Correlogram the flows

The autocorrelation was explored in the annual flows using the following formula:

$$r_k = \frac{c_k}{c_0} = \frac{\sum_{t=1}^{N-k} (X_t - \bar{X})(X_{t+k} - \bar{X})}{\sum_{t=1}^N (X_t - \bar{X})^2} \quad (\text{Equation 2.1.2-1})$$

Where:

$r_k$  is the lag-k autocorrelation coefficient;

$k$  is the la time lag in years;

$c_k$  is the autocovariance of the variable time-series, which is discharge in this case;

$c_0$  is the autocovariance for  $k = 0$ ;

$N$  is the length of the time-series in years;

$t = 1 \dots N$

$X_t$  is the discharge value for year  $t$ ;

$\bar{X}$  is the mean value of the time-series.

As shown in Table 2.1.2-1 and Figure 2.1.2-1, the annual minimum flows have a quasi-linear autocorrelation extending up to six years; those in the annual mean and maximum flows extend to 10 and 14 years respectively. There seems not to be any meaningful correlation between different flow types.

<b>Lag-K (Years)</b>	<b>Autocorrelation coefficients for Different discharge types</b>		
	Annual minimum	Annual mean	Annual mean
0	1	1	1
1	0.61	0.67	0.56
2	0.47	0.65	0.55
3	0.38	0.58	0.49
4	0.26	0.46	0.44
5	0.18	0.47	0.48
6	0.01	0.39	0.39
7		0.40	0.42
8		0.20	0.32
9		0.19	0.18
10		0.05	0.10
11			0.02
12			0.04
13			0.02
14			0.03

Table A-2.1.2-1: Autocorrelation coefficients of annual flows of the Niger River at Koulikoro, Mali

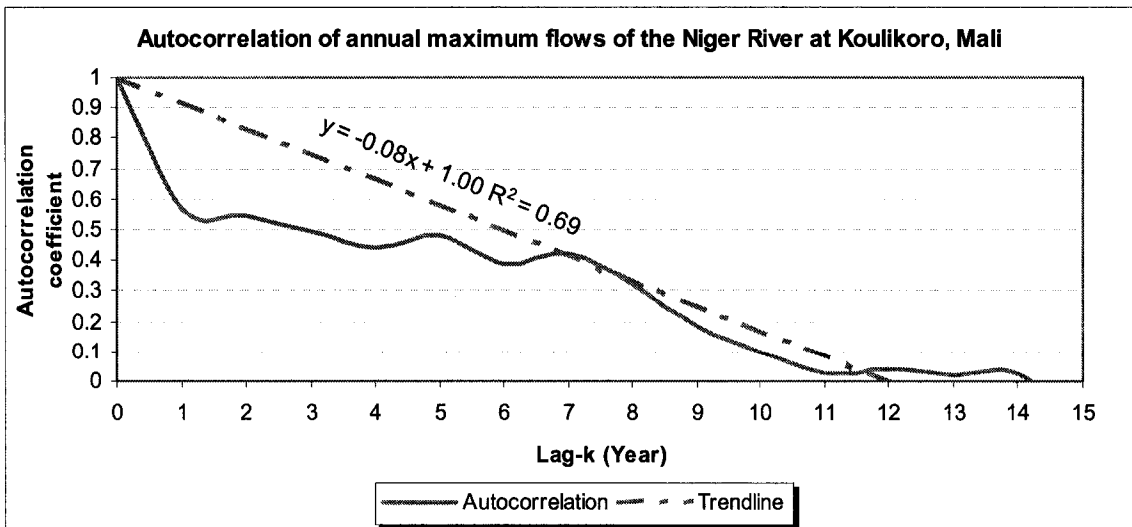
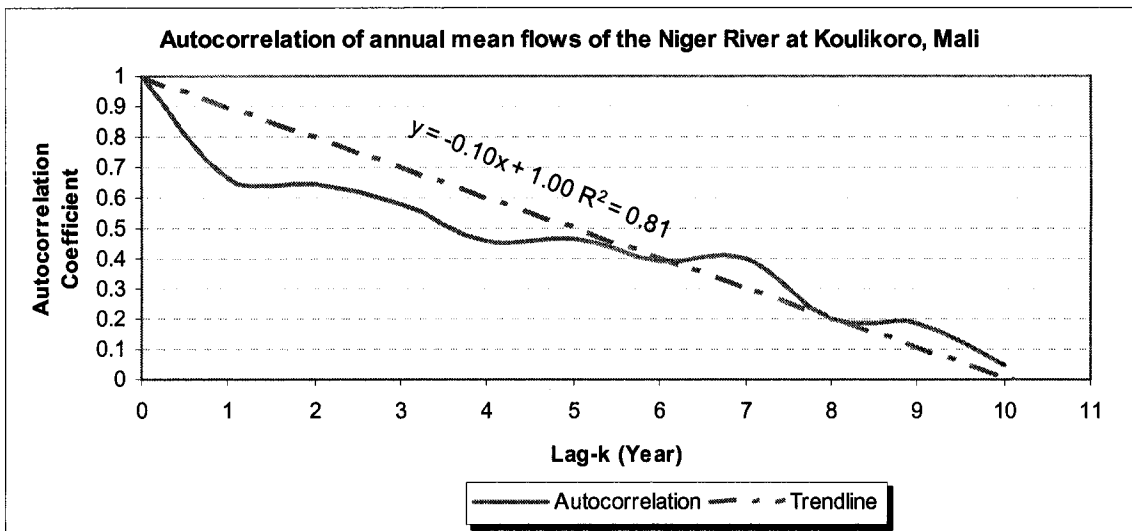
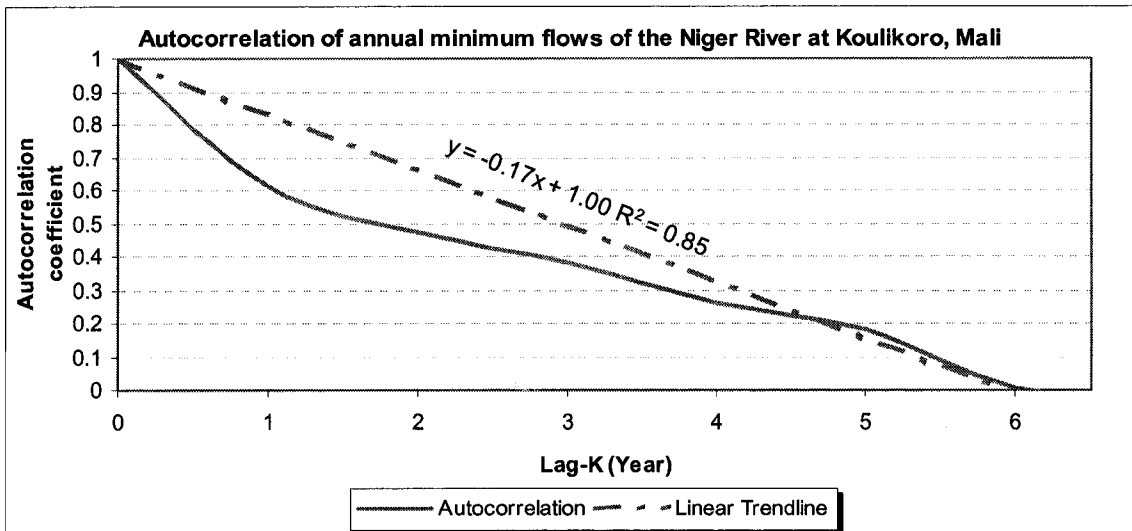


Figure A-2.1.2-1: Autocorrelation of flows of the Niger River at Koulikoro, Mali

## 2.2. THE BANİ RİVER AT DOUNA, MALİ

### 2.2.1. Annual flows

As shown by exponential decreasing trend in figure 2.2.1-1, all the annual flows of the Bani River have steadily been sustaining deficits since the early 1970s. Since 1983, the annual minimum flows have consistently been under one m<sup>3</sup>/s; in three particularly dry years (1985, 1987, 1988), the river went completely dry. The particularly high flows of 1994 were exceptional for the annual mean and annual maximum flows.

Statistics	Type of annual discharge		
	Minimum	Average	Maximum
Mean	11.75	416.82	1676.70
Standard Error	1.84	40.43	146.79
Median	8.29	362.56	1510
Standard Deviation	12.07	265.10	962.55
Sample Variance	145.61	70277.59	926508.45
Kurtosis	-0.57	-1.24	-1.35
Skewness	0.78	0.40	0.24
Coefficient of Variation	1.03	0.64	0.57
Range	41.5	845.32	3042
Minimum	0	69.99	288
Maximum	41.5	915.32	3330

Table A-2.2.1-3: Statistics of the annual flows of the Bani River at Douna, Mali

Here too, all the statistics (standard deviation, coefficient of variation) point toward a greater variability in the annual minimum flows compared to the other flow types of the Bani River.

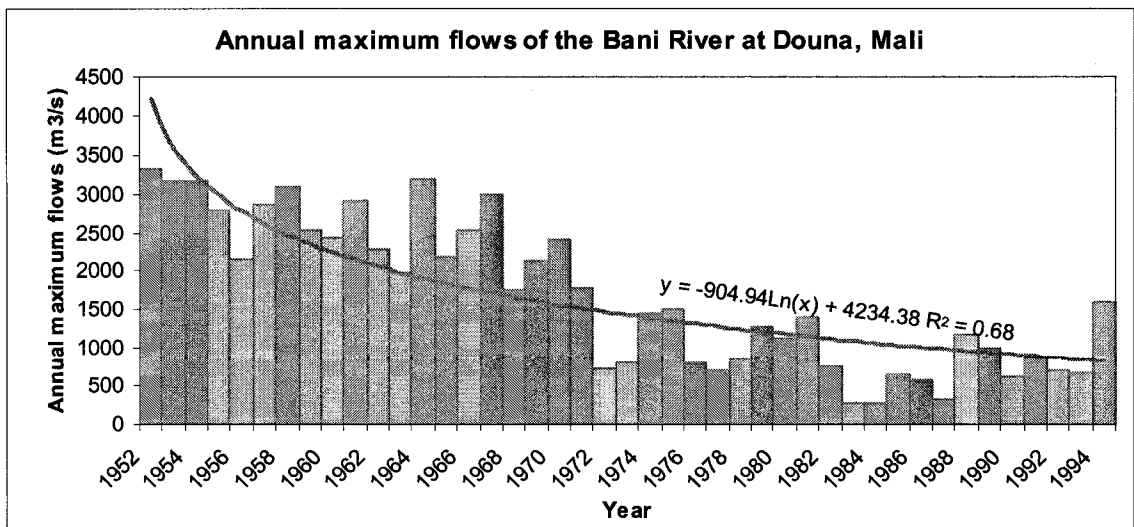
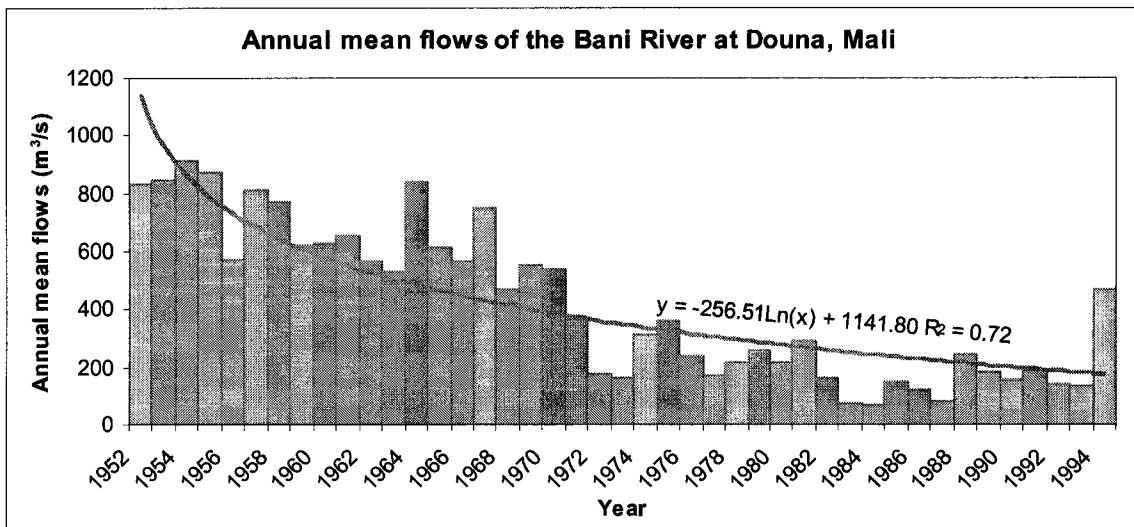
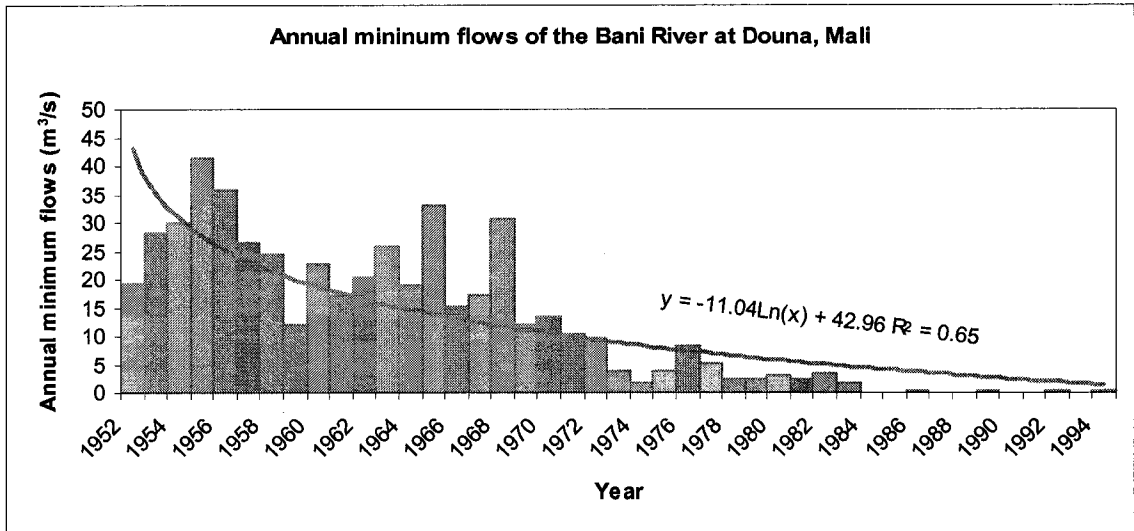


Figure A-2.2.1-1: Flows of the Bani River at Douna, Mali

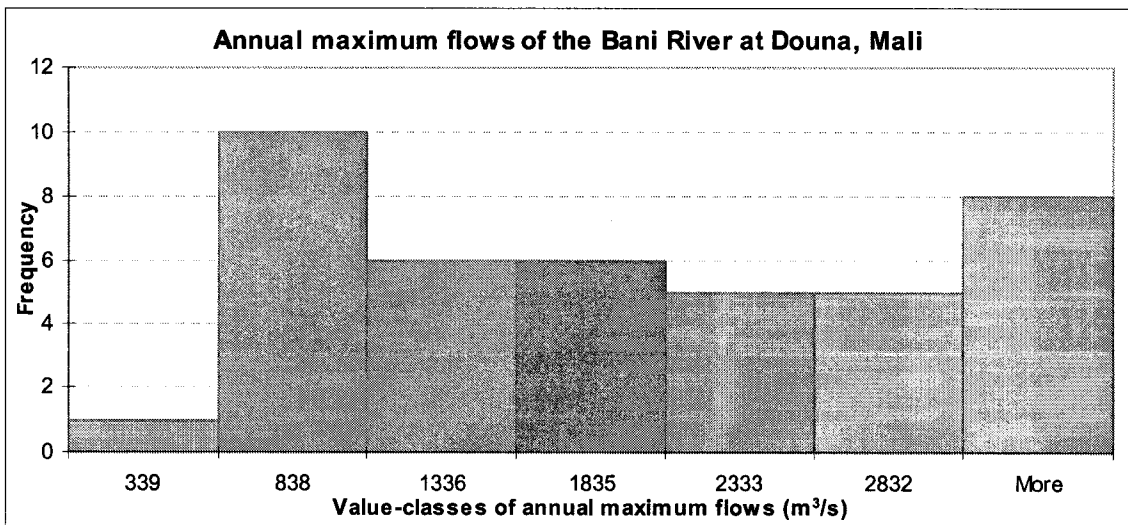
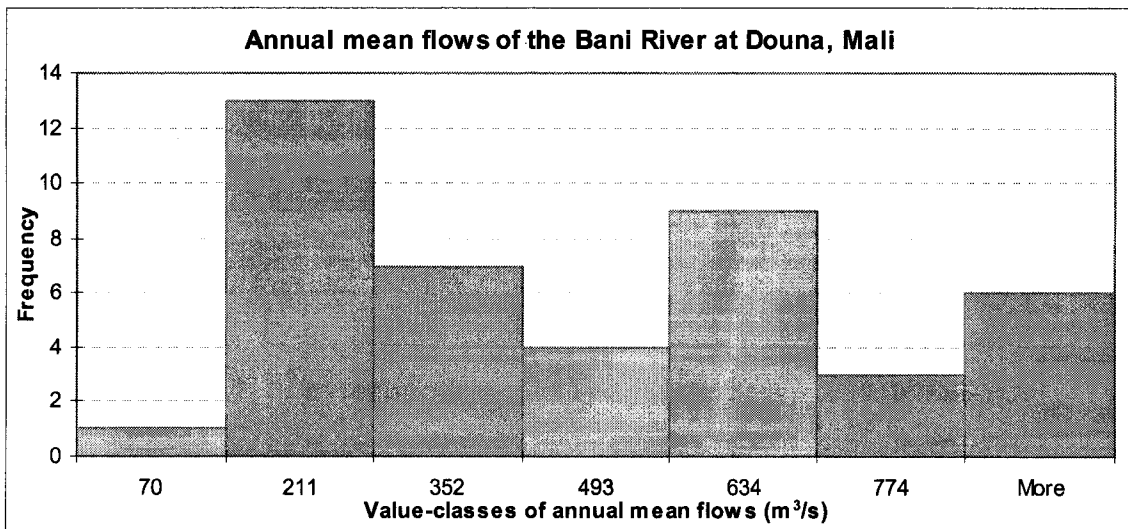
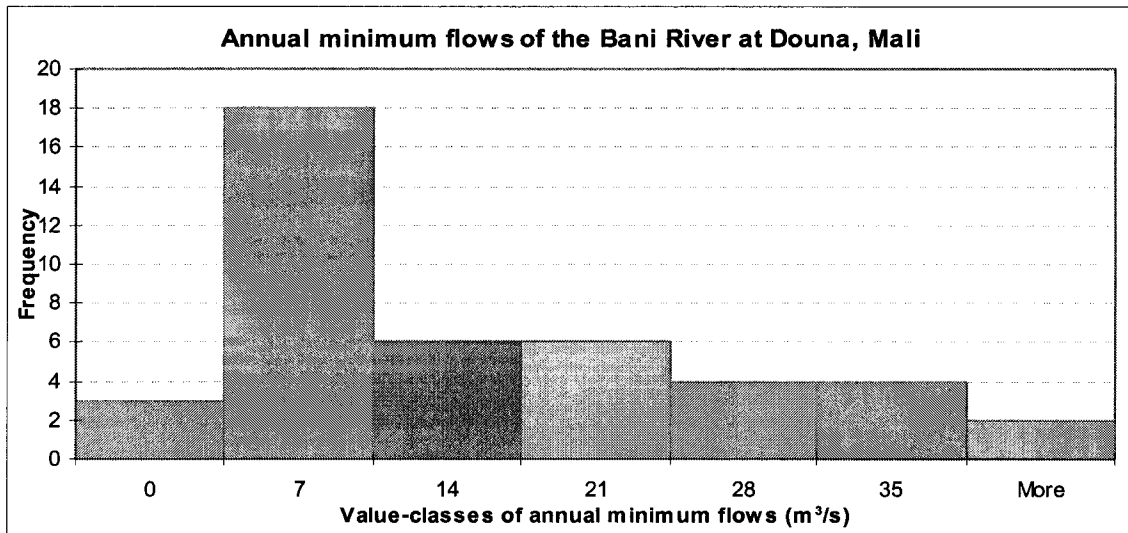


Figure A-2.2.1-2: Histograms of the flows of the Bani River at Douna, Mali

The beta probability distribution function was fitted to the data of annual flows. The initial values of the moment estimators of the parameters of the beta function were optimized by the least square method; their final values are:

- ✓  $\hat{\alpha} = 0.33$  and  $\hat{\beta} = 0.81$  for the annual minimum flows;
- ✓  $\hat{\alpha} = 0.61$  and  $\hat{\beta} = 0.87$  for the annual mean flows;
- ✓  $\hat{\alpha} = 0.67$  and  $\hat{\beta} = 0.81$  for the annual maximum flows.

The results of the fitting are shown in Table 2.2.1-2 and Figure 2.2.1-3.

Order	Annual Discharge (m <sup>3</sup> /s)			Return Period (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of			CDF of Fitted Distribution		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum Flows Beta	Annual Mean flows: Beta	Annual Maximum flows: Beta
1	0	69.99	288	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.00	0.00
2	0	73.02	288	1.02	1.05	1.02	0.02	0.02	0.02	0.00	0.03	0.00
3	0	84.68	339	1.02	1.07	1.07	0.02	0.02	0.07	0.00	0.08	0.05
4	0.02	120.36	590	1.10	1.10	1.10	0.09	0.09	0.09	0.07	0.16	0.18
5	0.06	139.09	640	1.13	1.13	1.13	0.11	0.11	0.11	0.10	0.20	0.20
6	0.11	144.31	657	1.16	1.16	1.16	0.14	0.14	0.14	0.12	0.21	0.20
7	0.13	148.43	688	1.19	1.19	1.19	0.16	0.16	0.16	0.13	0.21	0.21
8	0.27	157.43	701	1.22	1.22	1.22	0.18	0.18	0.18	0.17	0.23	0.22
9	0.39	161.80	701	1.26	1.26	1.22	0.20	0.20	0.18	0.19	0.23	0.22
10	0.47	164.66	729	1.29	1.29	1.29	0.23	0.23	0.23	0.20	0.24	0.23
11	0.51	168.01	753	1.33	1.33	1.33	0.25	0.25	0.25	0.21	0.24	0.24
12	1.62	176.37	806	1.38	1.38	1.38	0.27	0.27	0.27	0.31	0.26	0.26
13	1.69	185.47	815	1.42	1.42	1.42	0.30	0.30	0.30	0.31	0.27	0.26
14	2.27	194.25	858	1.47	1.47	1.47	0.32	0.32	0.32	0.34	0.28	0.27
15	2.44	215.44	875	1.52	1.52	1.52	0.34	0.34	0.34	0.35	0.31	0.28
16	2.54	217.54	1010	1.57	1.57	1.57	0.36	0.36	0.36	0.36	0.32	0.32
17	3.04	241.32	1120	1.63	1.63	1.63	0.39	0.39	0.39	0.38	0.35	0.36
18	3.52	247.86	1190	1.69	1.69	1.69	0.41	0.41	0.41	0.40	0.35	0.38
19	3.88	259.27	1280	1.76	1.76	1.76	0.43	0.43	0.43	0.41	0.37	0.41
20	3.95	296.19	1420	1.83	1.83	1.83	0.45	0.45	0.45	0.42	0.41	0.45
21	5.01	314.88	1450	1.91	1.91	1.91	0.48	0.48	0.48	0.45	0.43	0.45
22	8.29	362.56	1510	2.00	2.00	2.00	0.50	0.50	0.50	0.54	0.48	0.47
23	9.8	369.58	1610	2.10	2.10	2.10	0.52	0.52	0.52	0.57	0.49	0.50
24	10.4	468.25	1770	2.20	2.20	2.20	0.55	0.55	0.55	0.58	0.59	0.54
25	12	472.40	1790	2.32	2.32	2.32	0.57	0.57	0.57	0.61	0.59	0.55
26	12.2	530.02	1990	2.44	2.44	2.44	0.59	0.59	0.59	0.61	0.65	0.60
27	13.3	540.23	2130	2.59	2.59	2.59	0.61	0.61	0.61	0.63	0.66	0.64
28	15.1	551.48	2170	2.75	2.75	2.75	0.64	0.64	0.64	0.66	0.67	0.65
29	17.1	563.19	2190	2.93	2.93	2.93	0.66	0.66	0.66	0.69	0.68	0.66
30	17.1	566.29	2290	2.93	3.14	3.14	0.66	0.66	0.68	0.69	0.68	0.68
31	19	572.54	2410	3.38	3.38	3.38	0.70	0.70	0.70	0.72	0.69	0.72
32	19.3	613.29	2430	3.67	3.67	3.67	0.73	0.73	0.73	0.72	0.72	0.72
33	20.5	619.44	2540	4.00	4.00	4.00	0.75	0.75	0.75	0.74	0.73	0.75
34	22.6	629.93	2550	4.40	4.40	4.40	0.77	0.77	0.77	0.77	0.74	0.75
35	24.5	654.42	2800	4.89	4.89	4.89	0.80	0.80	0.80	0.79	0.76	0.82
36	25.7	750.38	2870	5.50	5.50	5.50	0.82	0.82	0.82	0.80	0.84	0.84
37	26.7	770.55	2920	6.29	6.29	6.29	0.84	0.84	0.84	0.82	0.86	0.86
38	28.4	809.78	3000	7.33	7.33	7.33	0.86	0.86	0.86	0.84	0.89	0.88
39	30.1	829.05	3080	8.80	8.80	8.80	0.89	0.89	0.89	0.86	0.91	0.90
40	30.8	836.03	3160	11.00	11.00	11.00	0.91	0.91	0.91	0.86	0.92	0.93
41	33	843.77	3170	14.67	14.67	14.67	0.93	0.93	0.93	0.89	0.93	0.93
42	35.8	874.63	3190	22.00	22.00	22.00	0.95	0.95	0.95	0.92	0.95	0.94
43	41.5	915.32	3330	44.00	44.00	44.00	0.98	0.98	0.98	1.00	1.00	1.00

Coefficient of determination R<sup>2</sup> =

0.99 0.98 0.99

Table A-2.2.1-2: Probability distributions of flows of the Bani River at Douna, Mali

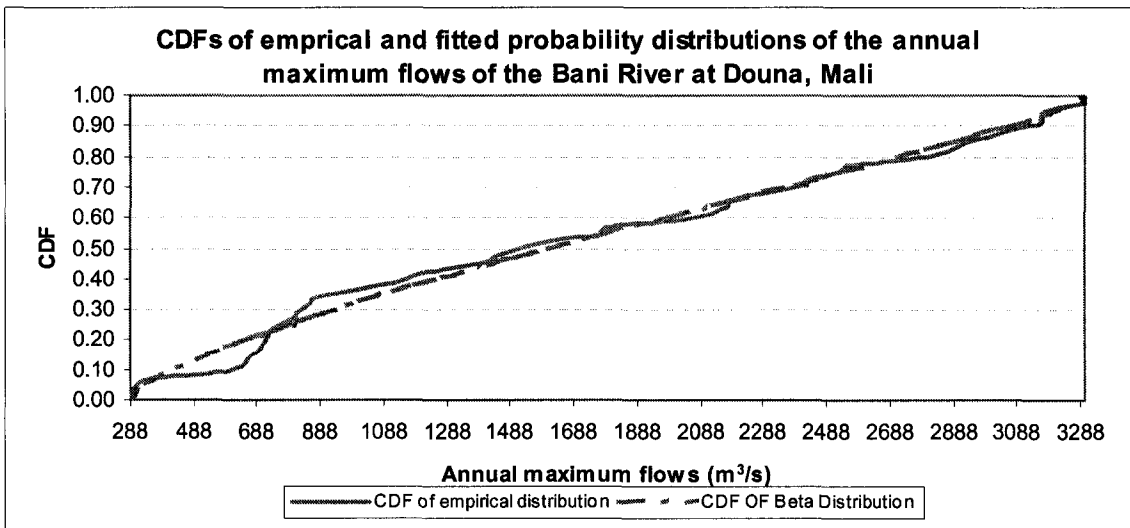
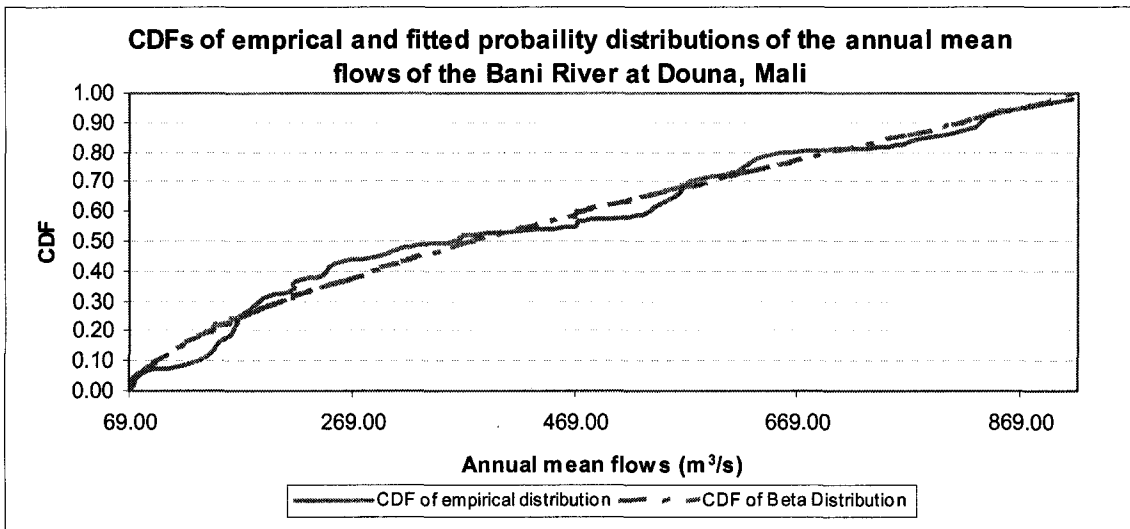
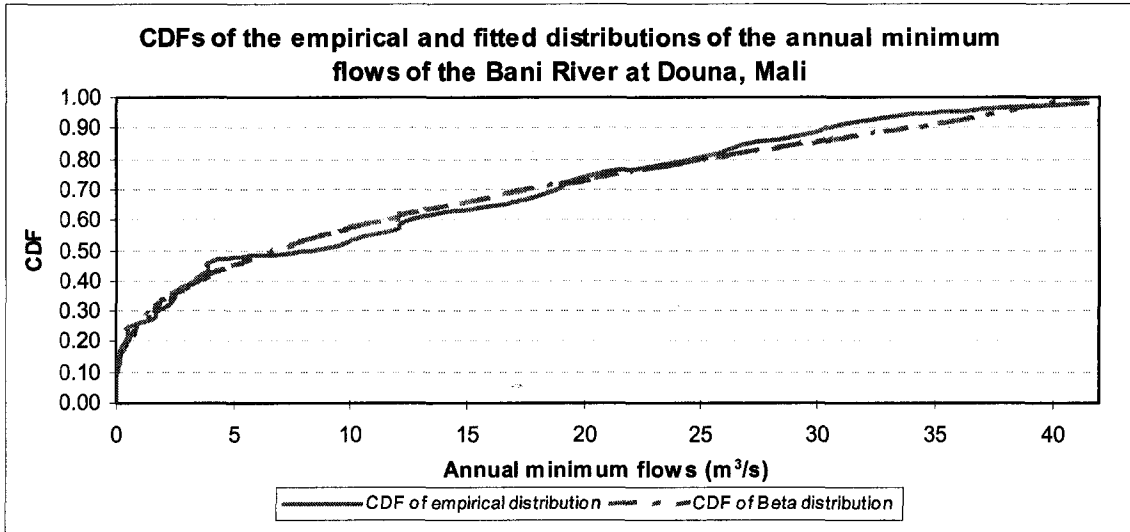


Figure A-2.2.1-3: CDFs of the probability distributions of the flows of the Bani River at Douna, Mali

## 2.2.2. Correlogram of flows

The computed correlation coefficients are given in Table 2.2.2-1, below.

Lag-K (Year)	Autocorrelation coefficients for different discharges		
	Annual Minimum	Annual Mean	Annual maximum
0	1	1	1
1	0.85	0.87	0.84
2	0.82	0.82	0.76
3	0.78	0.86	0.82
4	0.70	0.80	0.76
5	0.76	0.78	0.75
6	0.67	0.79	0.76
7	0.75	0.73	0.69
8	0.74	0.65	0.63
9	0.69	0.69	0.66
10	0.73	0.70	0.64
11	0.65	0.65	0.58
12	0.70	0.66	0.59
13	0.64	0.63	0.57
14	0.65	0.56	0.52
15	0.58	0.50	0.47
16	0.43	0.41	0.33
17	0.54	0.33	0.32
18	0.40	0.17	0.21
19	0.37	0.03	0.07
20	0.43	0.01	-0.01
21	0.59		
22	0.50		
23	0.31		
24	0.24		
25	0.39		
26	0.58		
27	0.61		
28	0.21		
29	0.03		

Table A-2.2.2-1: Autocorrelation coefficients of flows of the Bani River at  
Douna, Mali

Unlike the autocorrelation coefficients of the annual flows of the Niger at Koulikoro gaging station, those of the flows of the Bani River at Douna gaging station seem not to exhibit a clear linear trend. There seems not to be any direct correlation between the different flow types. The fact that most of the streams forming the Bani River originate in the tropical zone with limited rainfall, and that the drainage basin of the Bani River upstream of Douna is relatively small may contribute the absence of strong correlations in flows.

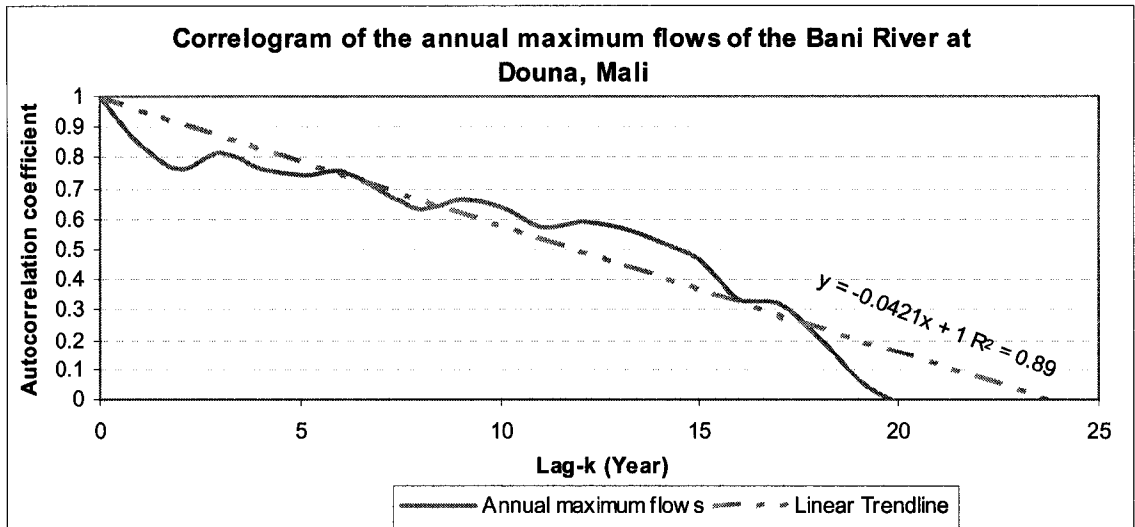
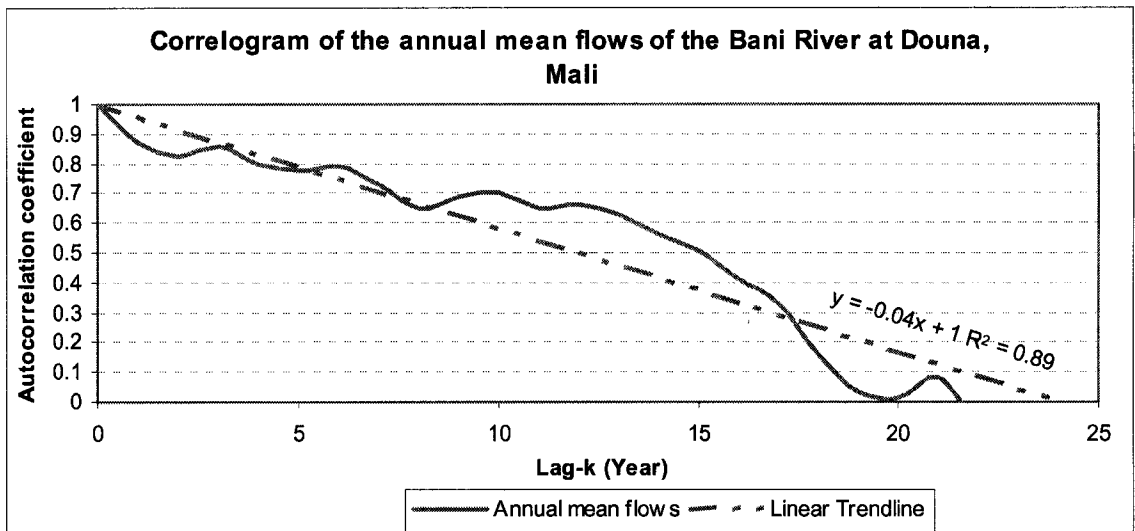
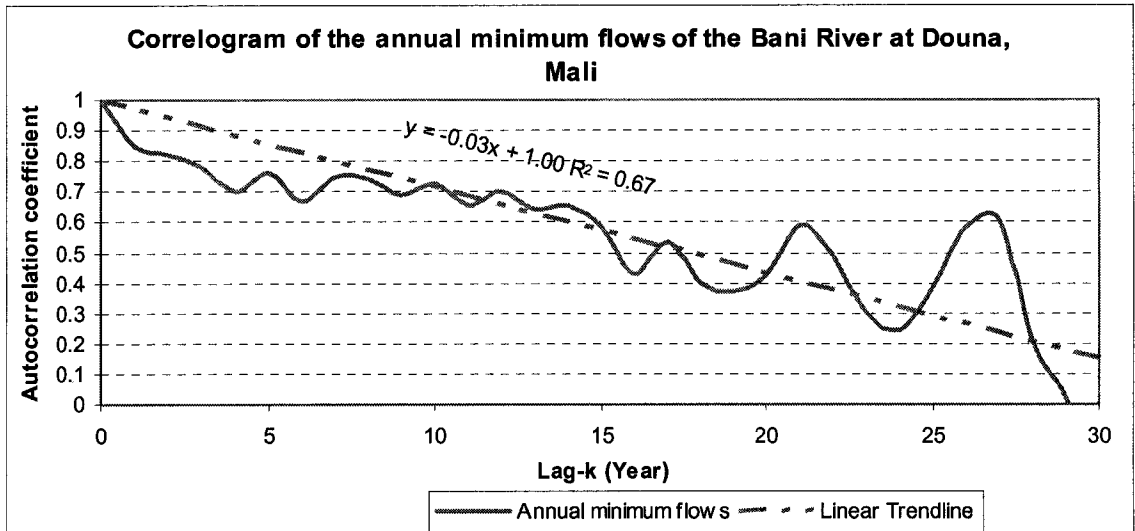


Figure A-2.2.2-1: Autocorrelation of flows of the Bani River at Koulikoro

## **2.3. THE NIGER RIVER'S DISTRIBUTARY AT MOPTI, MALI**

### **2.3.1. Annual flows: statistics and probability distribution**

The flows at this gaging station, like those at Koulikoro gaging station are all characterized by a very high seasonal and inter-annual variability.

<b>Statistics</b>	<b>Type of annual discharge</b>		
	Minimum	Average	Maximum
Mean	51.38	1003.01	2768.82
Standard Error	4.57	49.73	96.58
Median	49.4	1010.81	2910
Standard Deviation	32.62	355.14	689.71
Sample Variance	1064.07	126122.26	475702.59
Kurtosis	1.97	-1.08	-0.97
Skewness	1.24	0.06	-0.45
Coefficient of Variation	0.63	0.35	0.25
Range	151.58	1277.88	2470
Minimum	2.42	409.87	1290
Maximum	154	1687.75	3760

Table A-2.3.1-1: Statistics of Annual flows of the Niger River at Mopti, Mali

Compared to the other types of discharges, the annual minimum flows have a distribution skewed toward the large extreme values observed in the low flows in 1954, 1955 and 1956. The surge in the annual minimum flows in the mid-1950s is consistent with the trend observed at Koulikoro gaging station. While Figure 2.3.1-1 shows the graph of flows time series, Figure 2.31-2 shows the histograms of the three flow types.

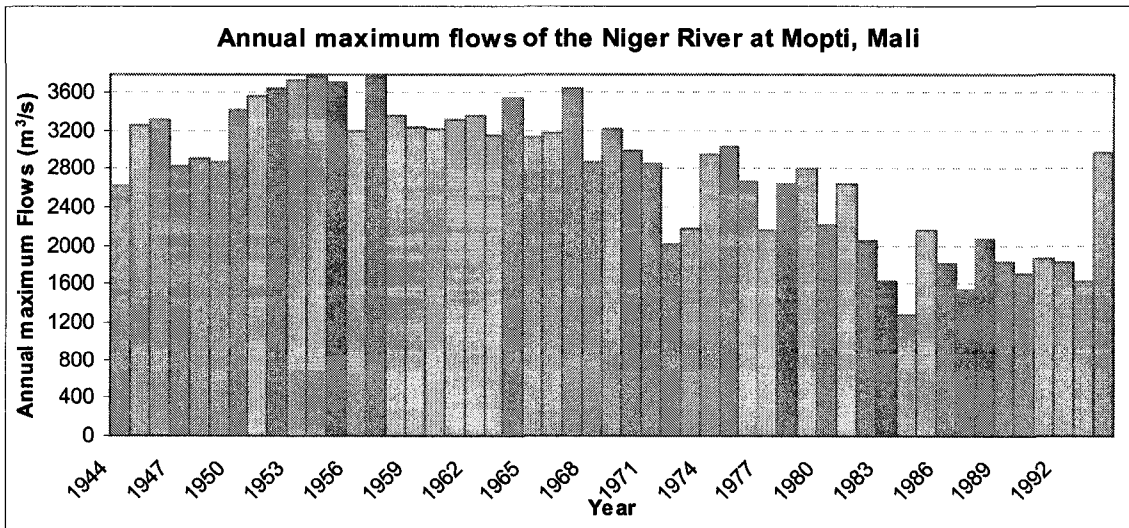
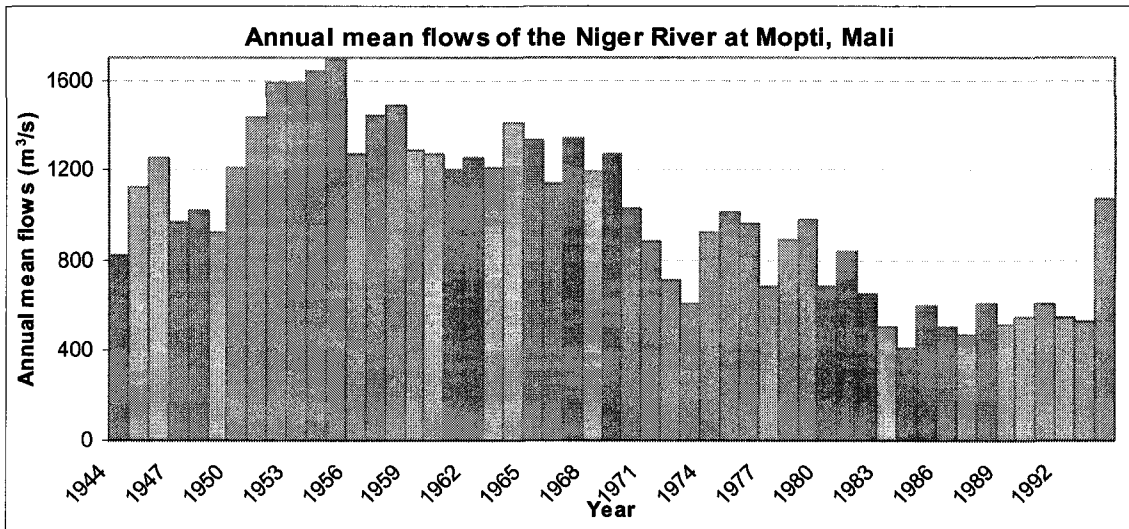
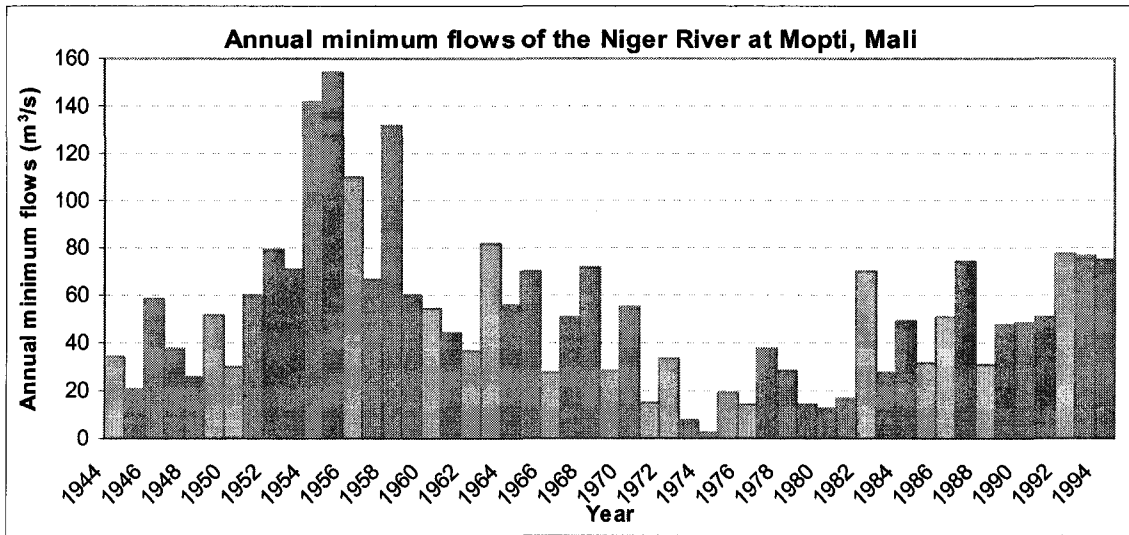


Figure A-2.3.1-1: Annual flows of the Niger River at Mopti, Mali

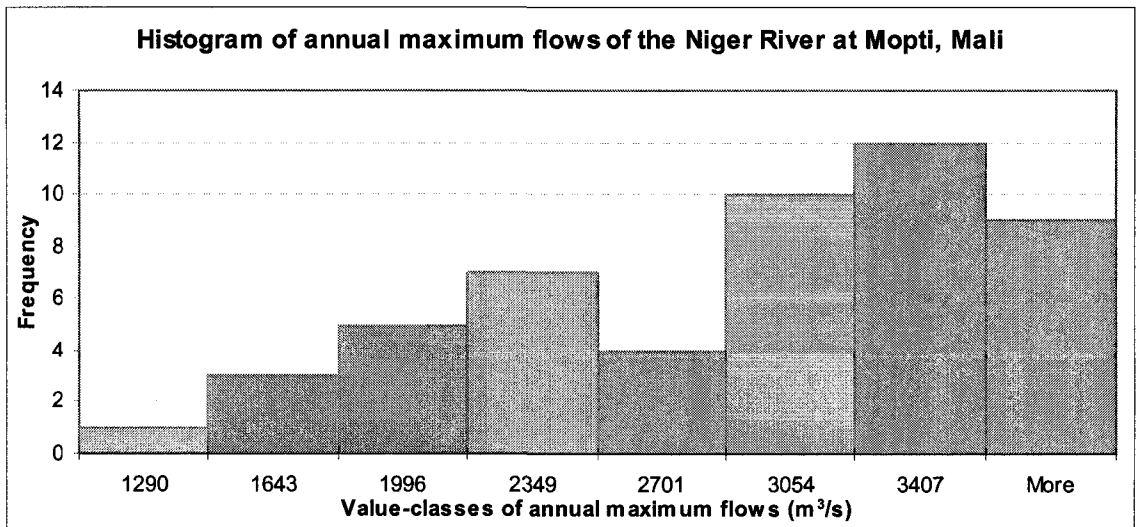
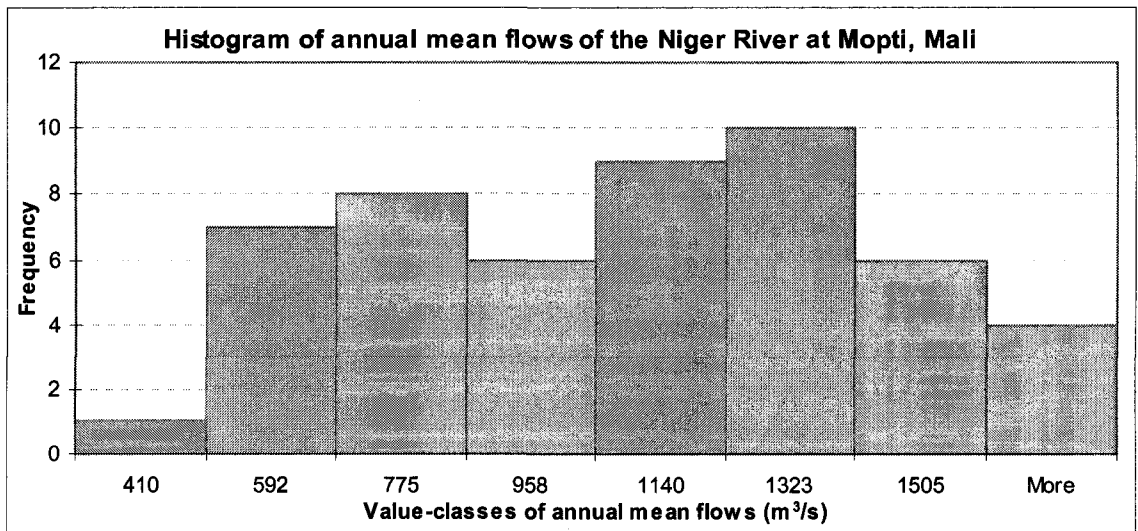
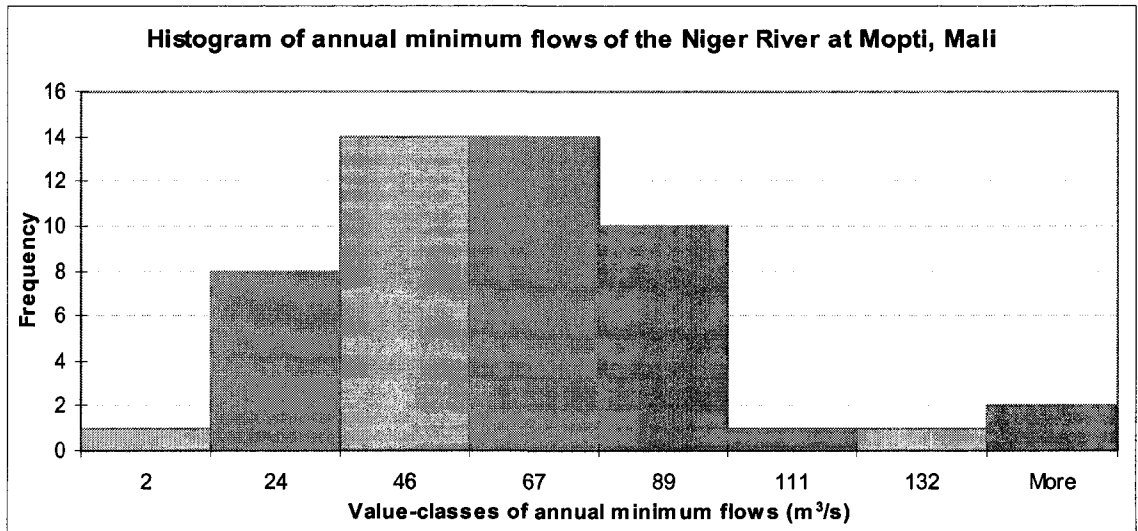


Figure A-2.3.1-2: Histograms of flows of the Bani River at Mopti, Mali

The gamma probability distribution function was fitted to the data of annual minimum flows; the parameters are  $\hat{\alpha} = 2.48$  and  $\hat{\beta} = 20.71$ . The normal probability function was fitted to the annual mean and maximum flows; all the results are given in Table 2.3.1-2 and Figure 2.3.1-4.

Order	Volume of deficits in Annual Discharge (m <sup>3</sup> /s)			Return Period of deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of deficits in			CDF of Fitted Distribution to deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Gamma	Annual Mean flows: Normal	Annual Maximum flows: Normal
1	2.42	409.87	1290	1.02	1.02	1.02	0.02	0.02	0.02	0.00	0.05	0.02
2	7.69	476.18	1550	1.04	1.04	1.04	0.04	0.04	0.04	0.02	0.07	0.04
3	12.1	504.35	1620	1.06	1.06	1.06	0.06	0.06	0.06	0.05	0.08	0.05
4	14.3	509.1	1630	1.08	1.08	1.08	0.08	0.08	0.08	0.08	0.08	0.05
5	14.4	516.61	1700	1.11	1.11	1.11	0.10	0.10	0.10	0.08	0.09	0.06
6	15.1	532.71	1810	1.13	1.13	1.13	0.12	0.12	0.12	0.08	0.09	0.08
7	16.7	547.28	1820	1.16	1.16	1.16	0.13	0.13	0.13	0.10	0.10	0.08
8	18.8	549.22	1830	1.18	1.18	1.18	0.15	0.15	0.15	0.13	0.10	0.09
9	20.8	597.81	1870	1.21	1.21	1.21	0.17	0.17	0.17	0.16	0.13	0.10
10	25.9	605.79	2010	1.24	1.24	1.24	0.19	0.19	0.19	0.23	0.13	0.14
11	27.1	610.73	2050	1.27	1.27	1.27	0.21	0.21	0.21	0.25	0.13	0.15
12	27.4	612.32	2080	1.30	1.30	1.30	0.23	0.23	0.23	0.25	0.14	0.16
13	28.4	650.43	2150	1.33	1.33	1.33	0.25	0.25	0.25	0.26	0.16	0.18
14	28.4	682.77	2160	1.33	1.37	1.37	0.25	0.27	0.27	0.26	0.18	0.19
15	30.3	686.97	2180	1.41	1.41	1.41	0.29	0.29	0.29	0.29	0.19	0.20
16	31.1	711.08	2210	1.44	1.44	1.44	0.31	0.31	0.31	0.31	0.21	0.21
17	31.4	822.07	2630	1.49	1.49	1.49	0.33	0.33	0.33	0.31	0.31	0.42
18	33.4	842.13	2650	1.53	1.53	1.53	0.35	0.35	0.35	0.34	0.33	0.43
19	34.1	880.3	2650	1.58	1.58	1.53	0.37	0.37	0.35	0.35	0.36	0.43
20	37	888.73	2670	1.63	1.63	1.63	0.38	0.38	0.38	0.39	0.37	0.44
21	37.8	924.65	2810	1.68	1.68	1.68	0.40	0.40	0.40	0.40	0.41	0.52
22	37.9	925.18	2820	1.73	1.73	1.73	0.42	0.42	0.42	0.41	0.41	0.53
23	44.1	963.97	2850	1.79	1.79	1.79	0.44	0.44	0.44	0.49	0.46	0.55
24	47.6	971.51	2860	1.86	1.86	1.86	0.46	0.46	0.46	0.54	0.46	0.55
25	48	981.58	2870	1.93	1.93	1.93	0.48	0.48	0.48	0.54	0.48	0.56
26	49.4	1010.8	2910	2.00	2.00	2.00	0.50	0.50	0.50	0.56	0.51	0.58
27	51	1019.9	2950	2.08	2.08	2.08	0.52	0.52	0.52	0.58	0.52	0.60
28	51.1	1028.1	2960	2.17	2.17	2.17	0.54	0.54	0.54	0.58	0.53	0.61
29	51.2	1071.1	2990	2.26	2.26	2.26	0.56	0.56	0.56	0.58	0.58	0.63
30	51.3	1125.9	3030	2.36	2.36	2.36	0.58	0.58	0.58	0.58	0.64	0.65
31	54.4	1139.8	3120	2.48	2.48	2.48	0.60	0.60	0.60	0.62	0.65	0.69

Table A-2.3.1-2: Probability distributions of flows of the Niger River at Mopti, Mali

Order	Volume of deficits in Annual Discharge (m <sup>3</sup> /s)			Return Period of deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of deficits in			CDF of Fitted Distribution to deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Gamma	Annual Mean flows: Normal	Annual Maximum flows: Normal
32	54.9	1194	3150	2.60	2.60	2.60	0.62	0.62	0.62	0.62	0.70	0.71
33	55.8	1202	3180	2.74	2.74	2.74	0.63	0.63	0.63	0.63	0.71	0.72
34	58.3	1206.3	3190	2.89	2.89	2.89	0.65	0.65	0.65	0.66	0.72	0.73
35	60.2	1210.5	3220	3.06	3.06	3.06	0.67	0.67	0.67	0.68	0.72	0.74
36	60.3	1249.5	3220	3.25	3.25	3.06	0.69	0.69	0.67	0.68	0.76	0.74
37	66.5	1252.7	3230	3.47	3.47	3.47	0.71	0.71	0.71	0.74	0.76	0.75
38	69.7	1267	3260	3.71	3.71	3.71	0.73	0.73	0.73	0.76	0.77	0.76
39	69.9	1271.5	3310	4.00	4.00	4.00	0.75	0.75	0.75	0.76	0.78	0.78
40	71	1273.2	3320	4.33	4.33	4.33	0.77	0.77	0.77	0.77	0.78	0.79
41	71.3	1290.2	3350	4.73	4.73	4.73	0.79	0.79	0.79	0.77	0.79	0.80
42	74.1	1328.2	3360	5.20	5.20	5.20	0.81	0.81	0.81	0.79	0.82	0.80
43	74.8	1340.9	3410	5.78	5.78	5.78	0.83	0.83	0.83	0.80	0.83	0.82
44	76.8	1407.8	3540	6.50	6.50	6.50	0.85	0.85	0.85	0.81	0.87	0.87
45	77.7	1433.7	3560	7.43	7.43	7.43	0.87	0.87	0.87	0.82	0.89	0.87
46	78.9	1438.9	3630	8.67	8.67	8.67	0.88	0.88	0.88	0.82	0.89	0.89
47	81.7	1487.3	3640	10.40	10.40	10.40	0.90	0.90	0.90	0.84	0.91	0.90
48	110	1584.4	3690	13.00	13.00	13.00	0.92	0.92	0.92	0.94	0.95	0.91
49	132	1587.8	3710	17.33	17.33	17.33	0.94	0.94	0.94	0.97	0.95	0.91
50	142	1641.4	3750	26.00	26.00	26.00	0.96	0.96	0.96	0.98	0.96	0.92
51	154	1687.8	3760	52.00	52.00	52.00	0.98	0.98	0.98	0.99	0.97	0.92
Coefficient of determination R <sup>2</sup> =										0.98	0.98	0.94

Table 2.3.1-2 (Continued): CDFs of probability distributions of flows of the Niger River at Mopti, Mali

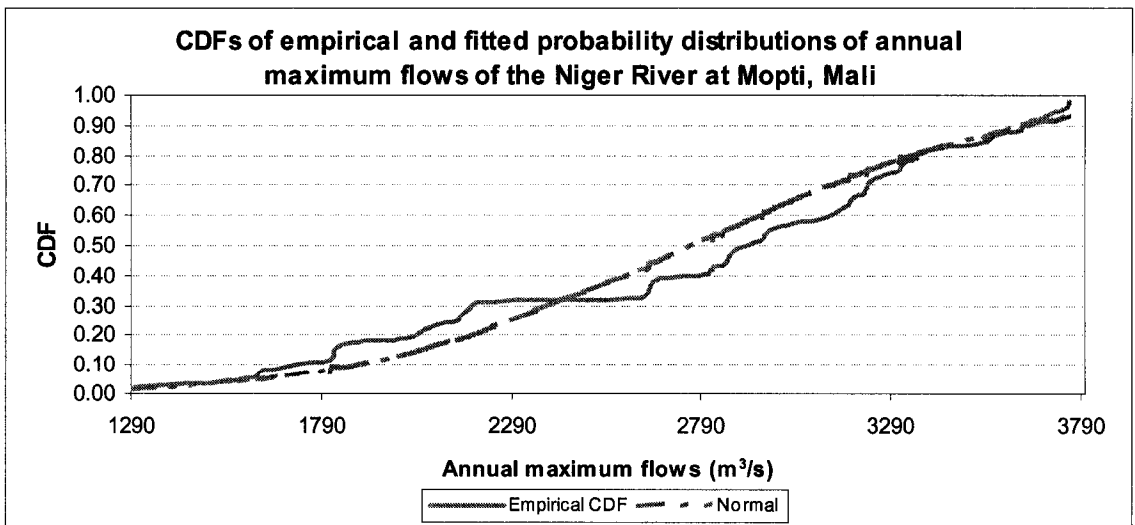
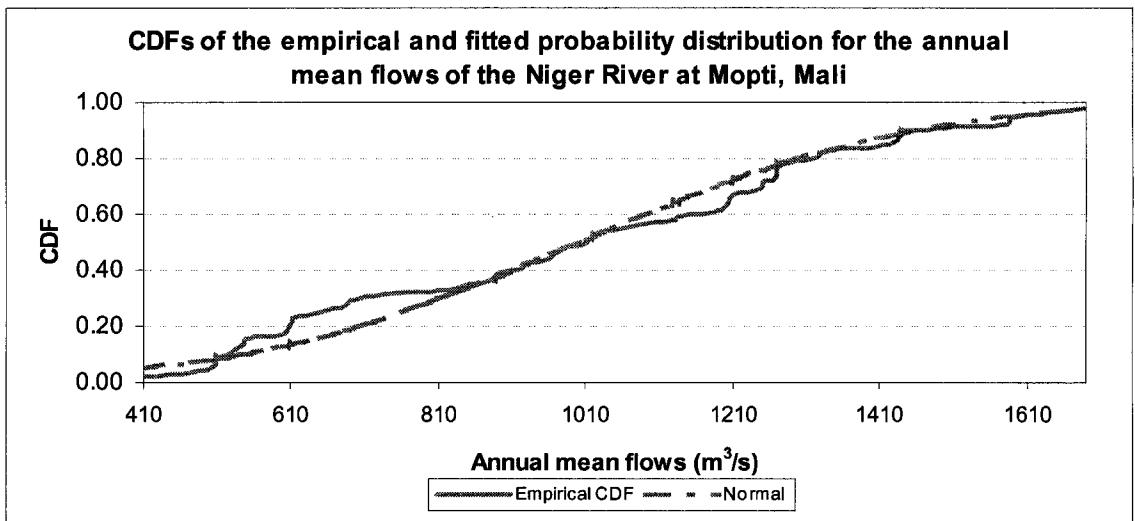
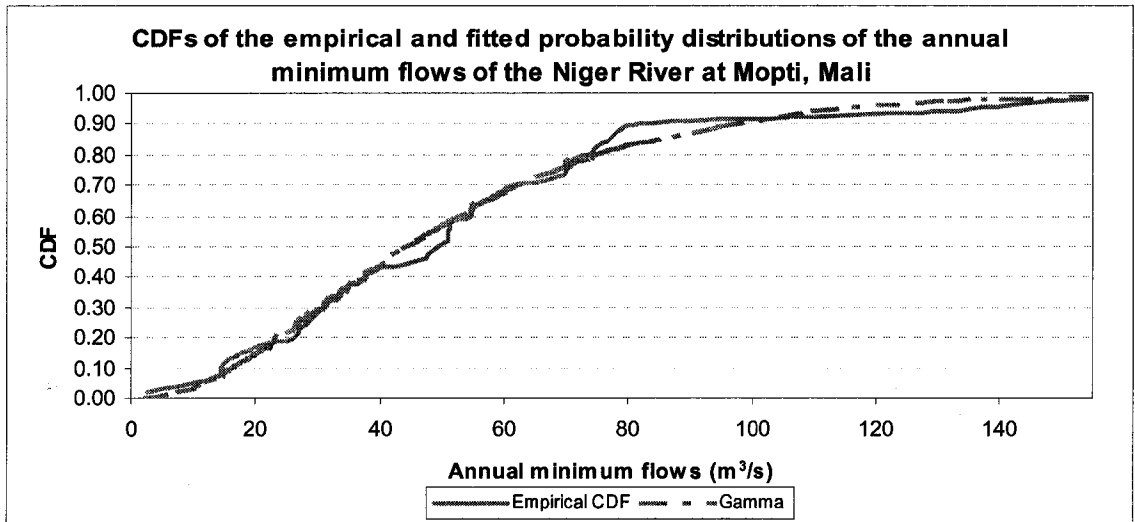


Figure A-2.3.1-3: CDFs of probability distributions of flows of the Niger River at Mopti, Mali

### 2.3.2. Correlogram of flows

For the different flow types, the coefficients of autocorrelation of the annual minimum flows at this gaging station are as shown in Table 2.3.2-1.

Lag-K (Years)	Autocorrelation coefficients for different discharges		
	Annual Minimum	Annual Mean	Annual maximum
0	1.00	1	1.00
1	0.58	0.87	0.80
2	0.53	0.80	0.74
3	0.44	0.76	0.75
4	0.29	0.69	0.72
5	0.28	0.65	0.67
6	0.04	0.60	0.64
7	0.07	0.56	0.63
8		0.47	0.53
9		0.50	0.56
10		0.49	0.52
11		0.49	0.53
12		0.55	0.58
13		0.45	0.47
14		0.38	0.47
15		0.32	0.39
16		0.25	0.33
17		0.13	0.21
18		0.01	0.16
19			0.14
20			0.02

Table A-2.3.2-1: Autocorrelation of the annual flows of the Niger River at Mopti, Mali

The autocorrelation coefficients shown in Table 2.3.2-1, and the graphs in Figure 2.3.2-1, all suggest strong autocorrelation in the three flow types.

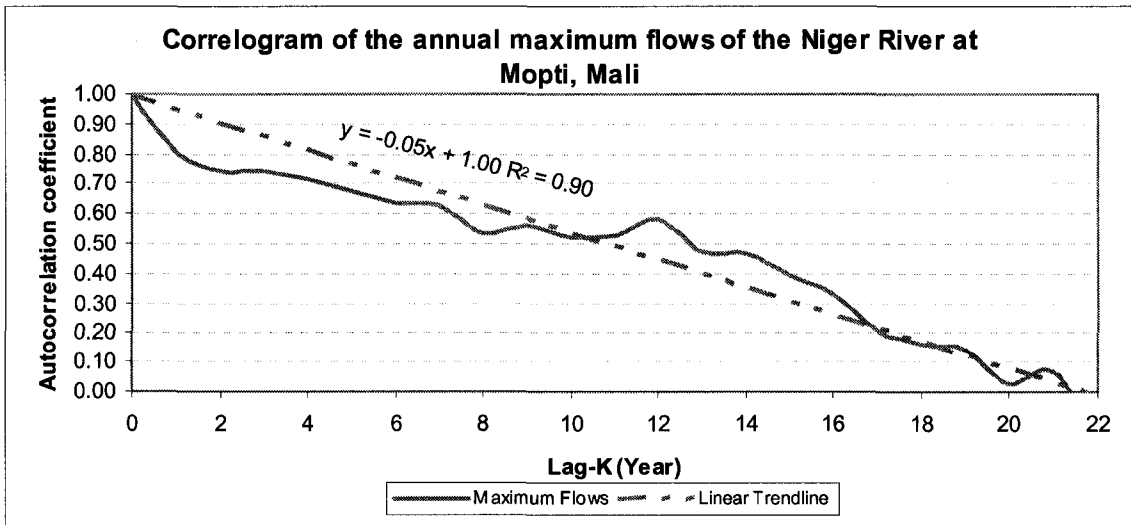
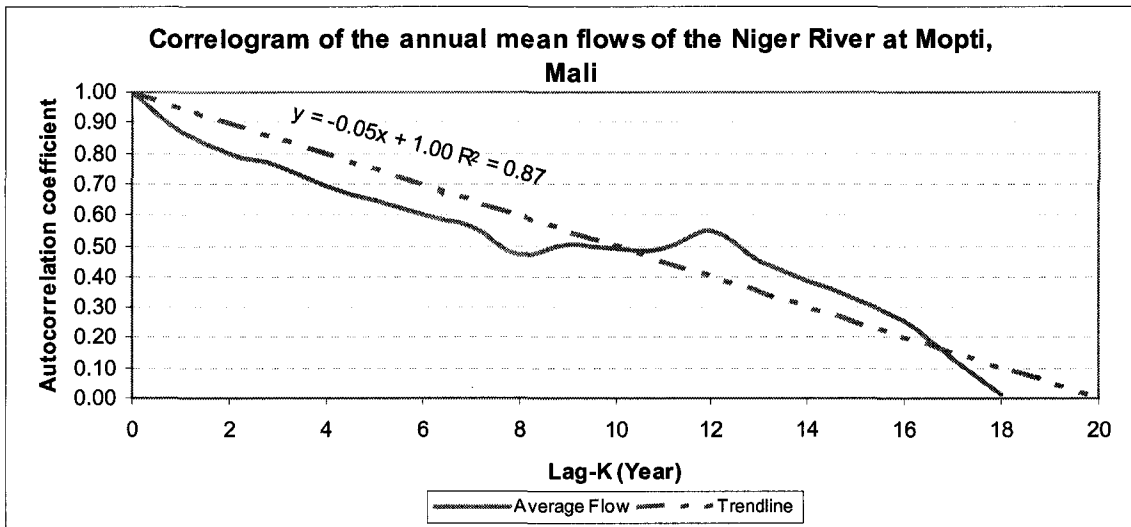
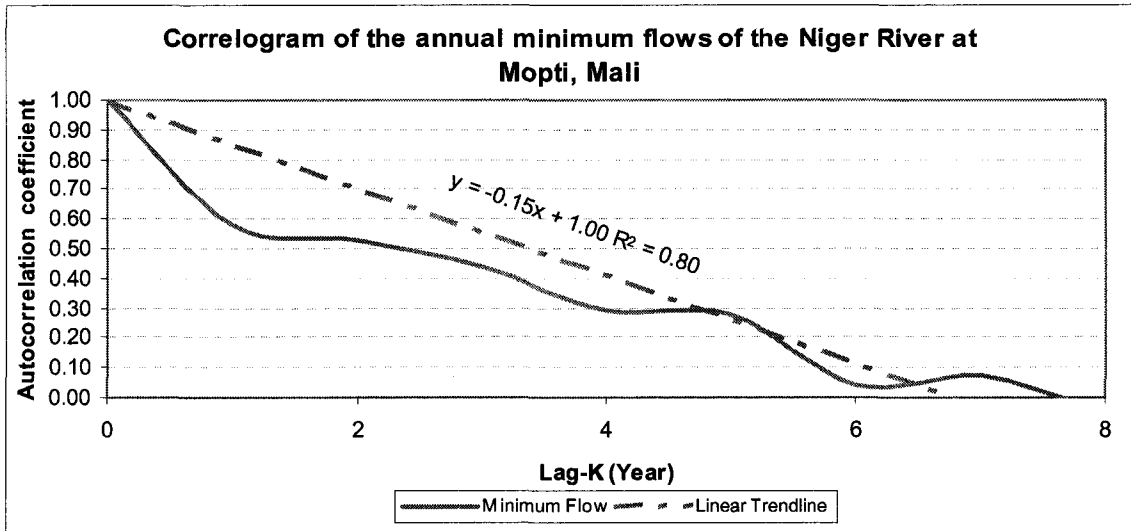


Figure A-2.3.2-1: Autocorrelation of flows of the Niger River at Mopti, Mali

## 2.4. THE ISSA BER AT DIRE, MALI

### 2.4.1. Annual flows

At this gaging station, the minimum flows have a wide range of variation going from its lowest value of 2.54 m<sup>3</sup>/s in 1945 to its highest recorded value of 215 m<sup>3</sup>/s in 1958. Compared to the other flow types, the annual minimum flows are characterized by a very high interannual variability (coefficient of variation of 1.1.)

Statistics	Type of annual discharge		
	Minimum	Average	Maximum
Mean	42.92	978.42	2062.82
Standard Error	5.59	31.67	40.69
Median	23.2	990.60	2180
Standard Deviation	47.12	266.82	342.90
Sample Variance	2219.86	71193.91	117577.67
Kurtosis	4.38	-0.69	-0.32
Skewness	2.10	-0.08	-0.67
Coefficient of Variation	1.10	0.27	0.17
Range	212.46	1101.70	1410
Minimum	2.54	454.05	1200
Maximum	215	1555.75	2610

Table A-2.4.1-1: Statistics of the annual flows of the Issa Ber at Dire, Mali

The lognormal probability distribution function is fitted to the annual minimum flows while the normal probability distribution is fitted to the other flow types. The results of the fitting are shown in Table 2.4.1-2 and Figure 2.4.1-3.

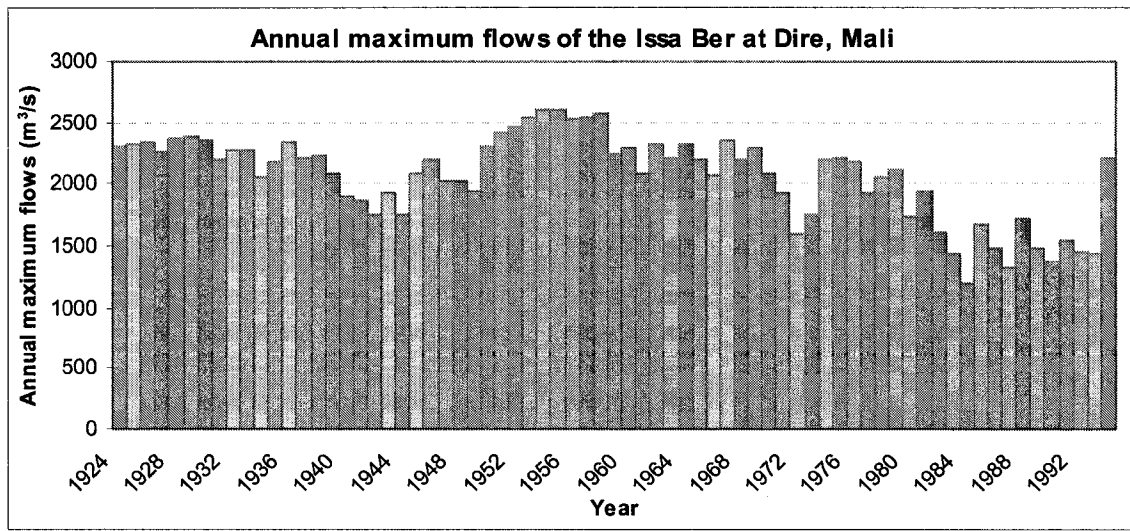
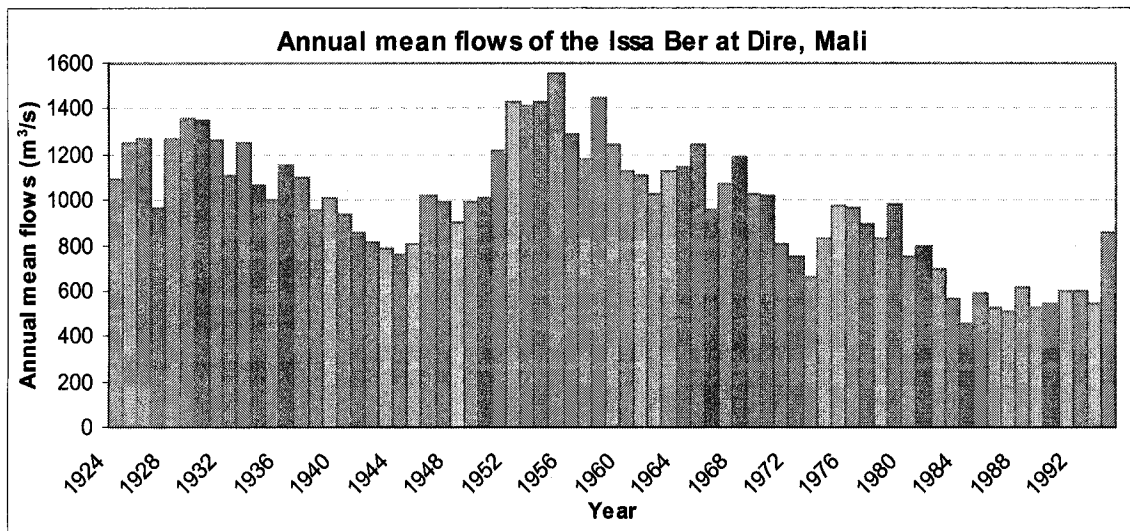
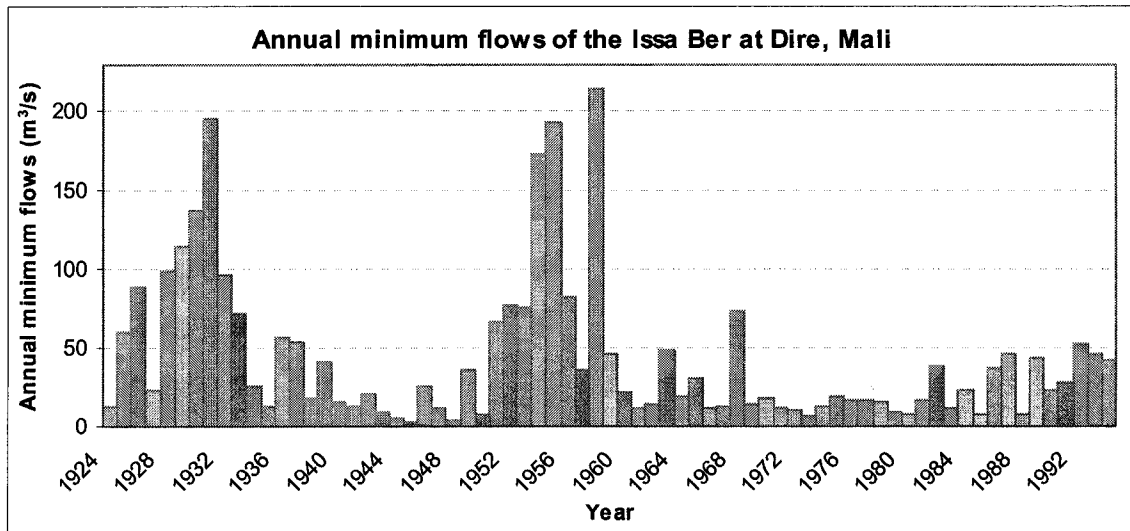


Figure A-2.4.1-1: Annual flows of the Issa Ber at Dire, Mali

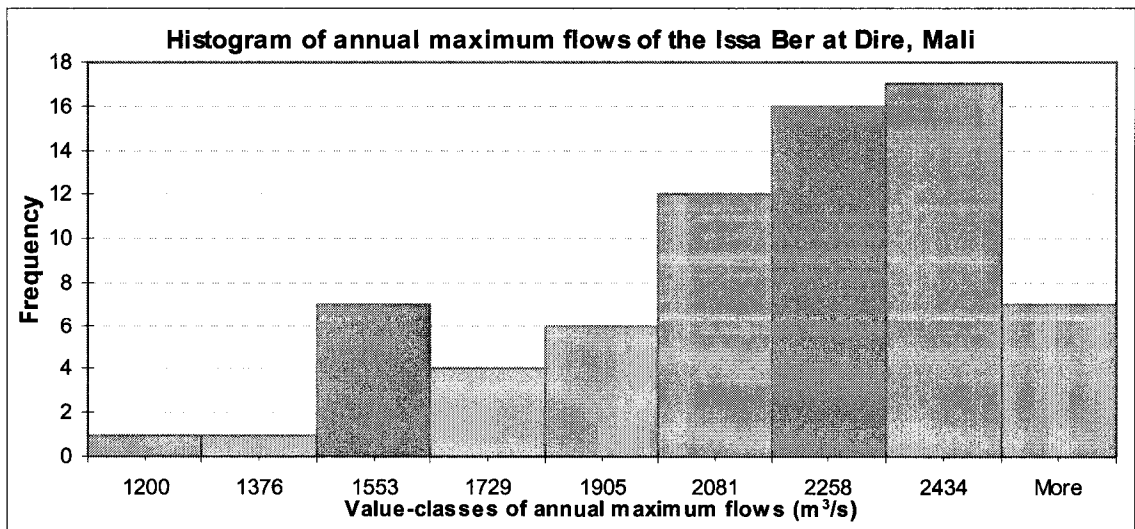
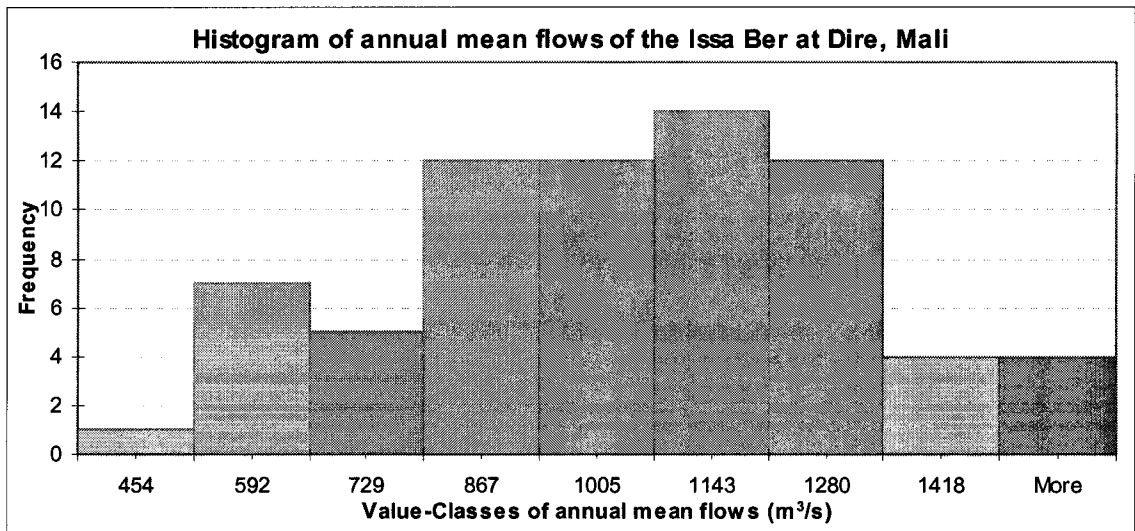
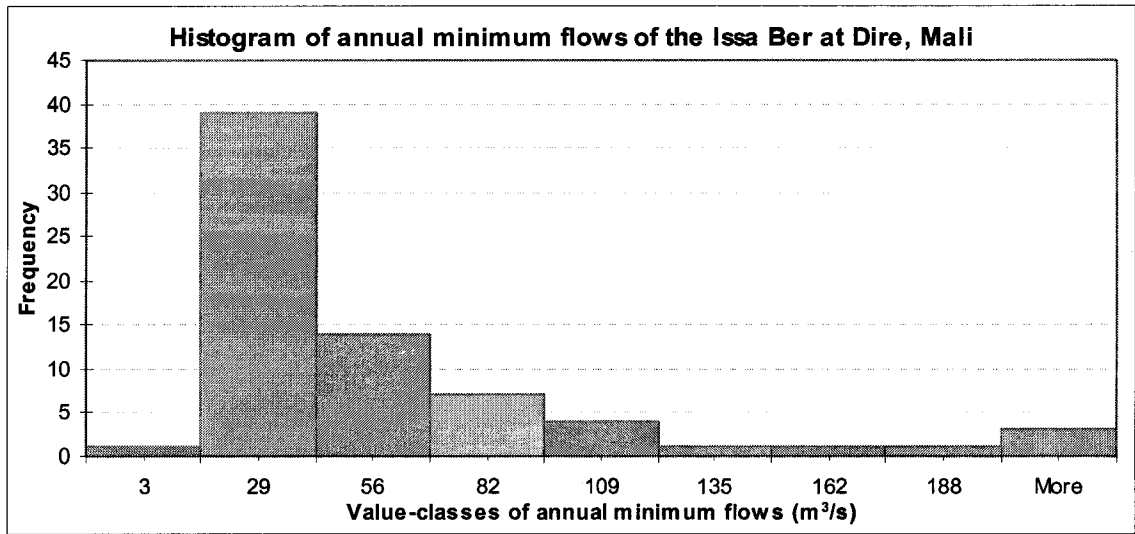


Figure A-2.4.1-2: Histograms of annual flows of the Issa Ber at Dire, Mali

Order	Volume of deficits in Annual Discharge (m <sup>3</sup> /s)			Return Period of deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of deficits in			CDF of Fitted Distribution to deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Lognormal	Annual Mean flows: Normal	Annual Maximum flows: Normal
1	2.54	454.05	1200	1.01	1.01	1.01	0.01	0.01	0.01	0.01	0.02	0.01
2	4.04	511.98	1320	1.03	1.03	1.03	0.03	0.03	0.03	0.03	0.04	0.02
3	4.53	524.26	1380	1.04	1.04	1.04	0.04	0.04	0.04	0.04	0.04	0.02
4	6.13	528.42	1440	1.06	1.06	1.06	0.06	0.06	0.06	0.07	0.05	0.03
5	7.37	547.75	1440	1.07	1.07	1.06	0.07	0.07	0.06	0.10	0.05	0.03
6	7.7	549.43	1460	1.09	1.09	1.09	0.08	0.08	0.08	0.11	0.05	0.04
7	7.72	564.27	1480	1.11	1.11	1.11	0.10	0.10	0.10	0.11	0.06	0.04
8	8.29	589.41	1490	1.13	1.13	1.13	0.11	0.11	0.11	0.12	0.07	0.05
9	8.41	597.38	1550	1.14	1.14	1.14	0.13	0.13	0.13	0.12	0.08	0.07
10	9.48	602.81	1590	1.16	1.16	1.16	0.14	0.14	0.14	0.15	0.08	0.08
11	10.8	613.08	1610	1.18	1.18	1.18	0.15	0.15	0.15	0.18	0.09	0.09
12	11.1	662.98	1680	1.20	1.2	1.20	0.17	0.17	0.17	0.19	0.12	0.13
13	11.2	694.56	1720	1.22	1.22	1.22	0.18	0.18	0.18	0.19	0.14	0.16
14	11.5	746.48	1730	1.24	1.24	1.24	0.19	0.19	0.19	0.20	0.19	0.17
15	11.7	749.60	1750	1.26	1.26	1.26	0.21	0.21	0.21	0.20	0.20	0.18
16	12.1	762.83	1750	1.29	1.29	1.26	0.22	0.22	0.21	0.21	0.21	0.18
17	12.5	784.34	1760	1.31	1.31	1.31	0.24	0.24	0.24	0.22	0.23	0.19
18	12.6	793.29	1860	1.33	1.33	1.33	0.25	0.25	0.25	0.23	0.24	0.28
19	12.6	804.74	1900	1.33	1.36	1.36	0.25	0.26	0.26	0.23	0.26	0.32
20	13	806.02	1920	1.38	1.38	1.38	0.28	0.28	0.28	0.24	0.26	0.34
21	13.4	815.98	1930	1.41	1.41	1.41	0.29	0.29	0.29	0.25	0.27	0.35
22	13.6	834.88	1930	1.44	1.44	1.41	0.31	0.31	0.29	0.25	0.30	0.35
23	14.4	835.26	1940	1.47	1.47	1.47	0.32	0.32	0.32	0.27	0.30	0.36
24	15.1	855.07	1940	1.50	1.5	1.47	0.33	0.33	0.32	0.29	0.32	0.36
25	15.6	861.54	2020	1.53	1.53	1.53	0.35	0.35	0.35	0.30	0.33	0.45
26	16.5	891.46	2020	1.57	1.57	1.53	0.36	0.36	0.35	0.32	0.37	0.45
27	16.6	900.58	2050	1.60	1.6	1.60	0.38	0.38	0.38	0.32	0.39	0.49
28	16.9	940.22	2060	1.64	1.64	1.64	0.39	0.39	0.39	0.33	0.44	0.50
29	18	953.22	2070	1.67	1.67	1.67	0.40	0.40	0.40	0.35	0.46	0.51
30	18.5	959.28	2080	1.71	1.71	1.71	0.42	0.42	0.42	0.36	0.47	0.52
31	19.6	965.92	2080	1.76	1.76	1.71	0.43	0.43	0.42	0.38	0.48	0.52
32	19.7	969.53	2090	1.80	1.8	1.80	0.44	0.44	0.44	0.38	0.49	0.53
33	20.2	977.15	2090	1.85	1.85	1.80	0.46	0.46	0.44	0.39	0.50	0.53
34	21.7	986.77	2120	1.89	1.89	1.89	0.47	0.47	0.47	0.42	0.51	0.57
35	23.1	990.13	2180	1.95	1.95	1.95	0.49	0.49	0.49	0.44	0.52	0.63
36	23.2	990.60	2180	2.00	2	1.95	0.50	0.50	0.49	0.45	0.52	0.63
37	23.3	1003.93	2190	2.06	2.06	2.06	0.51	0.51	0.51	0.45	0.54	0.64
38	25.7	1013.58	2190	2.12	2.12	2.06	0.53	0.53	0.51	0.49	0.55	0.64
39	26.1	1014.34	2190	2.18	2.18	2.06	0.54	0.54	0.51	0.49	0.55	0.64
40	28.7	1017.48	2200	2.25	2.25	2.25	0.56	0.56	0.56	0.53	0.56	0.66
41	30.7	1021.4	2200	2.32	2.32	2.25	0.57	0.57	0.56	0.56	0.56	0.66
42	35.3	1023.93	2210	2.40	2.4	2.40	0.58	0.58	0.58	0.61	0.57	0.67
43	36.2	1025.85	2210	2.48	2.48	2.40	0.60	0.60	0.58	0.62	0.57	0.67

Table A-2.4.1-2: Probability distributions of flows of the Issa Ber at Dire, Mali

Order	Volume of deficits in Annual Discharge (m <sup>3</sup> /s)			Return Period of deficit in (Year)			Non-Exceedance probability distributions					
	Minimum flows	Mean flows	Maximum flows	Minimum flows	Mean flows	Maximum flows	CDF of empirical Distribution of deficits in			CDF of Fitted Distribution to deficits in		
							Annual Minimum flows	Annual Mean flows	Annual Maximum flows	Annual Minimum flows: Lognormal	Annual Mean flows: Normal	Annual Maximum flows: Normal
44	37.4	1059.28	2210	2.57	2.57	2.40	0.61	0.61	0.58	0.64	0.62	0.67
45	38.3	1072.34	2210	2.67	2.67	2.40	0.63	0.63	0.58	0.64	0.64	0.67
46	41.5	1094.32	2220	2.77	2.77	2.77	0.64	0.64	0.64	0.67	0.67	0.68
47	42.4	1103.53	2250	2.88	2.88	2.88	0.65	0.65	0.65	0.68	0.68	0.71
48	43.7	1104.73	2260	3.00	3	3.00	0.67	0.67	0.67	0.69	0.68	0.72
49	46.3	1107.22	2270	3.13	3.13	3.13	0.68	0.68	0.68	0.71	0.69	0.73
50	46.3	1123.24	2270	3.13	3.27	3.13	0.68	0.69	0.68	0.71	0.71	0.73
51	46.6	1129.39	2290	3.43	3.43	3.43	0.71	0.71	0.71	0.72	0.71	0.75
52	49	1145.65	2290	3.60	3.6	3.43	0.72	0.72	0.71	0.73	0.73	0.75
53	52.8	1154.63	2300	3.79	3.79	3.79	0.74	0.74	0.74	0.76	0.75	0.76
54	54.3	1183.49	2300	4.00	4	3.79	0.75	0.75	0.74	0.77	0.78	0.76
55	56.5	1190.55	2320	4.24	4.24	4.24	0.76	0.76	0.76	0.78	0.79	0.77
56	60.3	1214.96	2320	4.50	4.5	4.24	0.78	0.78	0.76	0.80	0.81	0.77
57	66.5	1240.36	2320	4.80	4.8	4.24	0.79	0.79	0.76	0.82	0.84	0.77
58	71.5	1246.73	2330	5.14	5.14	5.14	0.81	0.81	0.81	0.84	0.84	0.78
59	73.2	1250.46	2340	5.54	5.54	5.54	0.82	0.82	0.82	0.85	0.85	0.79
60	74.9	1252.53	2350	6.00	6	6.00	0.83	0.83	0.83	0.85	0.85	0.80
61	76.4	1256.5	2360	6.55	6.55	6.55	0.85	0.85	0.85	0.86	0.85	0.81
62	82.3	1267.87	2370	7.20	7.2	7.20	0.86	0.86	0.86	0.87	0.86	0.81
63	88.4	1268.07	2390	8.00	8	8.00	0.88	0.88	0.88	0.89	0.86	0.83
64	95.8	1283.86	2410	9.00	9	9.00	0.89	0.89	0.89	0.90	0.87	0.84
65	98.8	1345.5	2470	10.29	10.29	10.29	0.90	0.90	0.90	0.91	0.92	0.88
66	114	1359.92	2530	12.00	12	12.00	0.92	0.92	0.92	0.93	0.92	0.91
67	137	1415.66	2540	14.40	14.4	14.40	0.93	0.93	0.93	0.95	0.95	0.92
68	172	1426.42	2550	18.00	18	18.00	0.94	0.94	0.94	0.97	0.95	0.92
69	193	1427.7	2580	24.00	24	24.00	0.96	0.96	0.96	0.98	0.95	0.93
70	196	1451.25	2600	36.00	36	36.00	0.97	0.97	0.97	0.98	0.96	0.94
71	215	1555.75	2610	72.00	72	72.00	0.99	0.99	0.99	0.98	0.98	0.94
Coefficient of determination R <sup>2</sup> =										0.99	0.99	0.94

Table A-2.4.1-2 (Continued): CDFs of probability distributions of flows of the Issa Ber at Dire, Mali

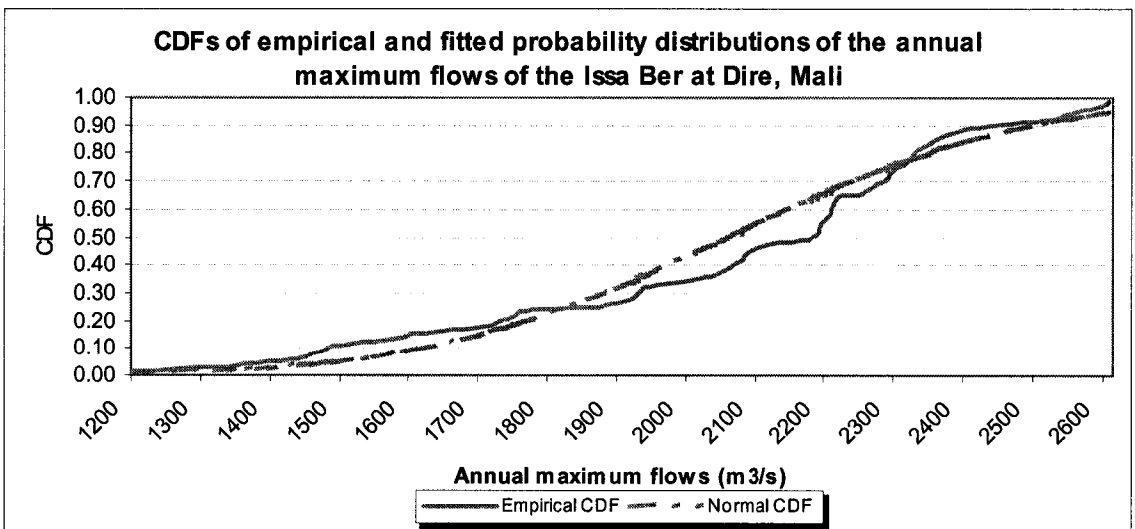
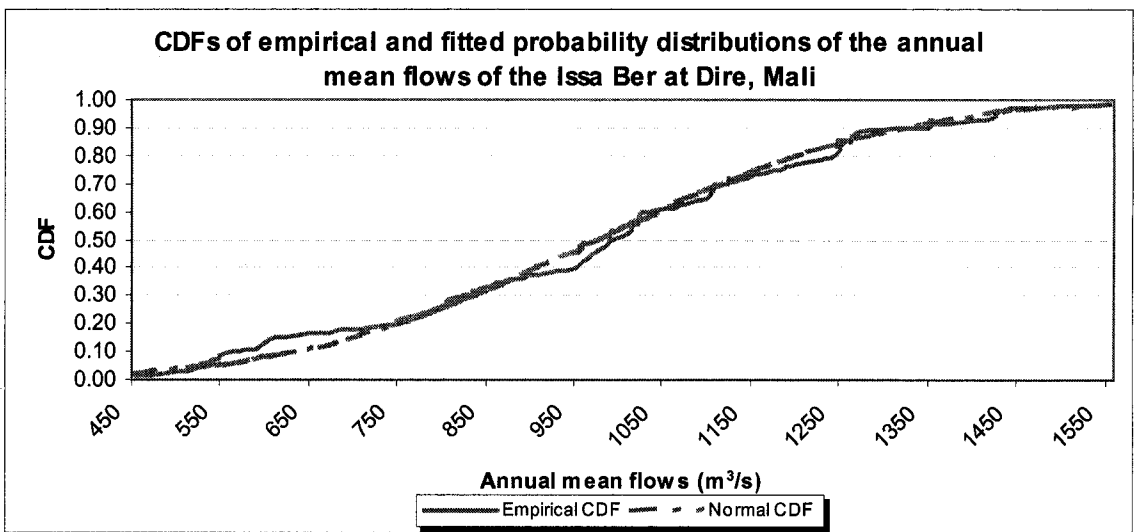
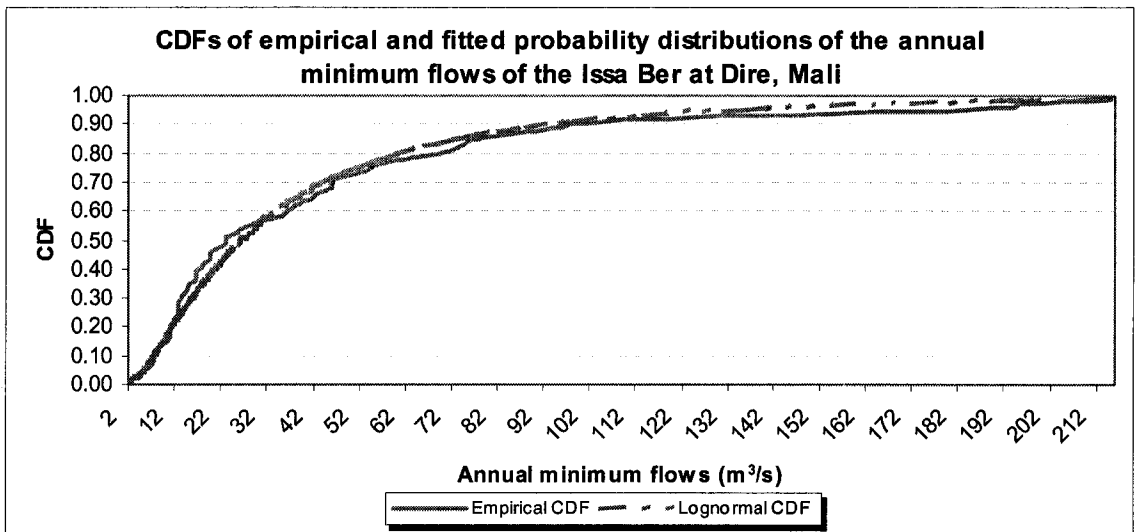


Figure A-2.4.1-3: CDFs of probability distributions of the annual flows of the Issa Ber at Dire, Mali

## 2.4.1 Correlogram

All the flow types show well-established linear autocorrelation extending up to 6 years for the annual minimum flows and to 14 years for the others; the strong and linear autocorrelation may be related to the direct influence of the return flows from the flood plains during periods of low flows. Similarly, there seems to be strong cross-correlation among the different flows, as shown in Table 2.4.1-1, and Figure 2.4.2-1 and Figure 2.4.2-2.

Lag-K (Years)	Autocorrelation coefficients for different discharges			Cross-correlation between different discharge types		
	Annual Minimum	Annual Mean	Annual maximum	Minimum-Mean	Minimum-Maximum	Mean-Maximum
0	1	1	1	0.62	0.45	0.92
1	0.54	0.87	0.82	0.48	0.40	0.80
2	0.39	0.80	0.74	0.42	0.39	0.75
3	0.41	0.76	0.68	0.41	0.31	0.70
4	0.23	0.67	0.59	0.34	0.32	0.64
5	0.14	0.60	0.54	0.30	0.26	0.56
6	0.01	0.55	0.51	0.26	0.27	0.54
7	-0.06	0.47	0.45	0.25	0.24	0.44
8		0.36	0.33	0.16	0.17	0.34
9		0.31	0.31	0.17	0.16	0.34
10		0.26	0.23	0.18	0.12	0.28
11		0.21	0.19	0.10	0.10	0.24
12		0.15	0.16	0.05	0.06	0.16
13		0.09	0.05	0.03	0.06	0.11
14		0.02	-0.02	0.00	0.00	0.04
15						0.06
16						0.05
17						0.04
18						0.01

Table 2.4.2-1: Autocorrelation and cross-correlation of flows of the Issa Ber at Dire, Mali

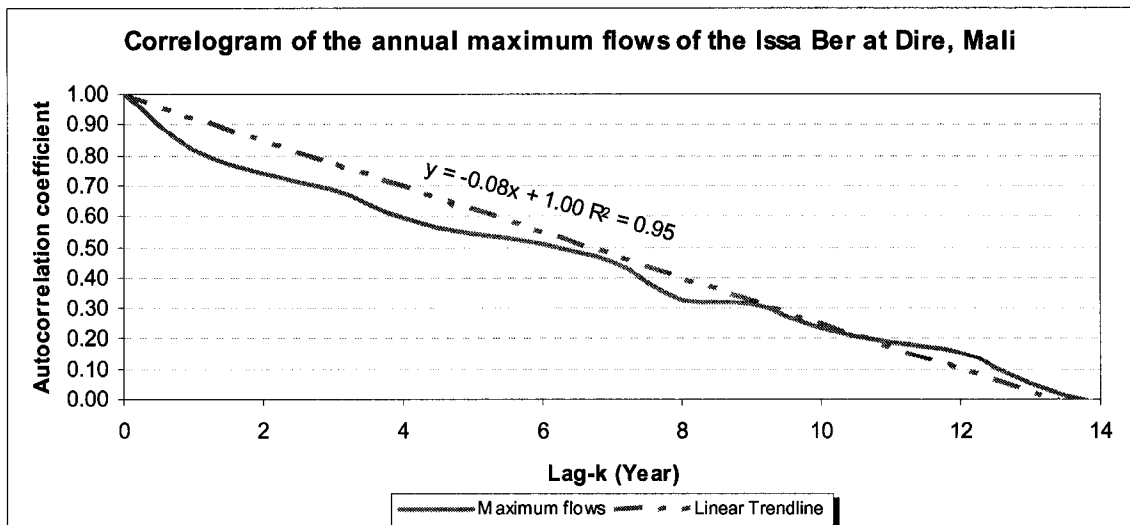
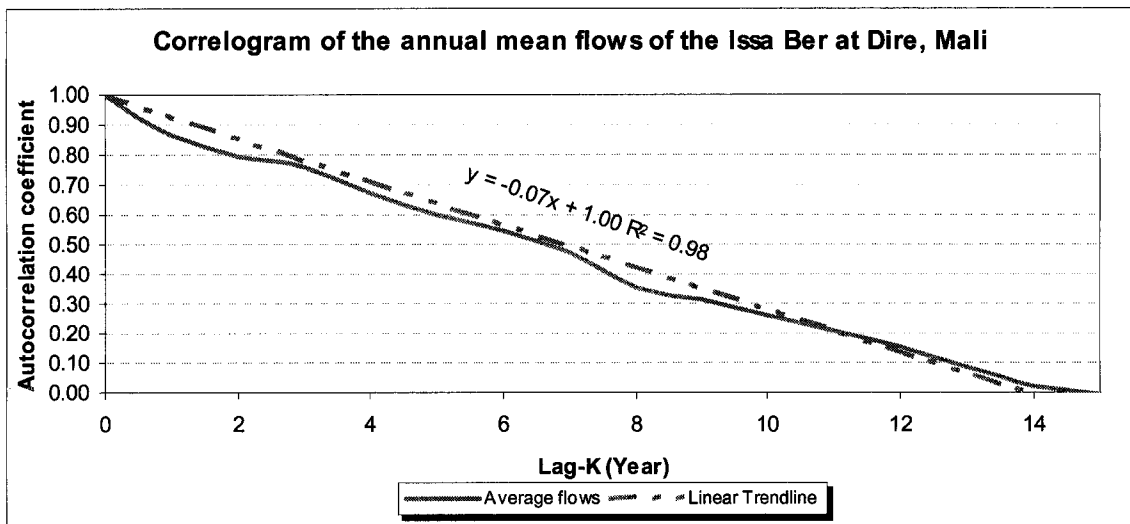
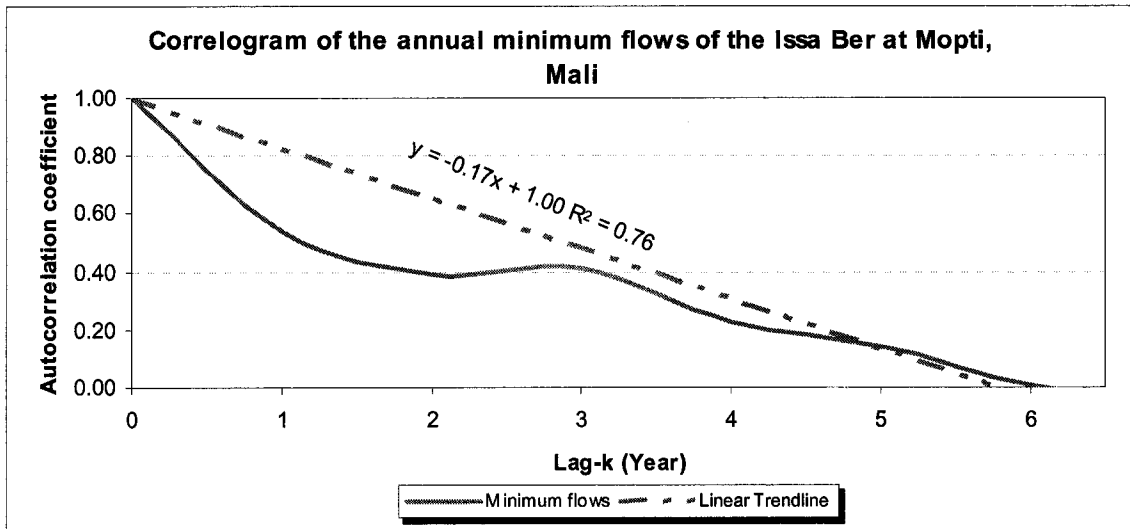


Figure A-2.4.2-1: Auto-correlation of flows of the Issa Ber at Dire, Mali

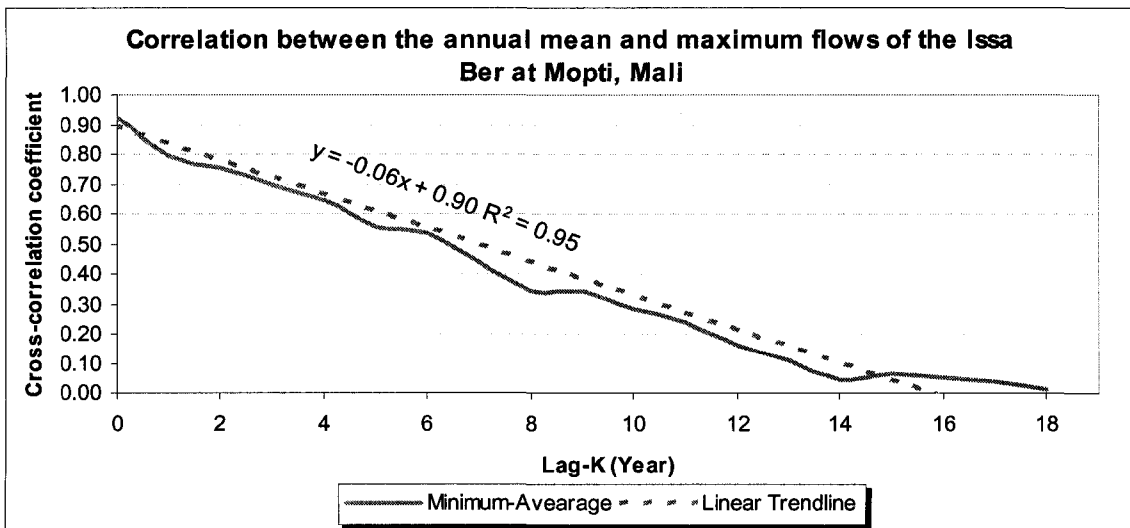
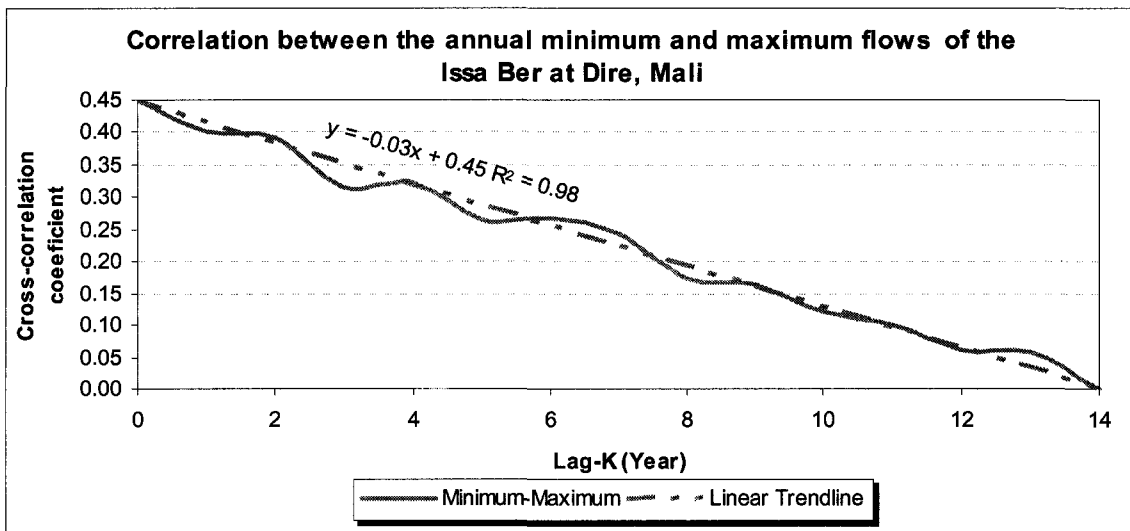
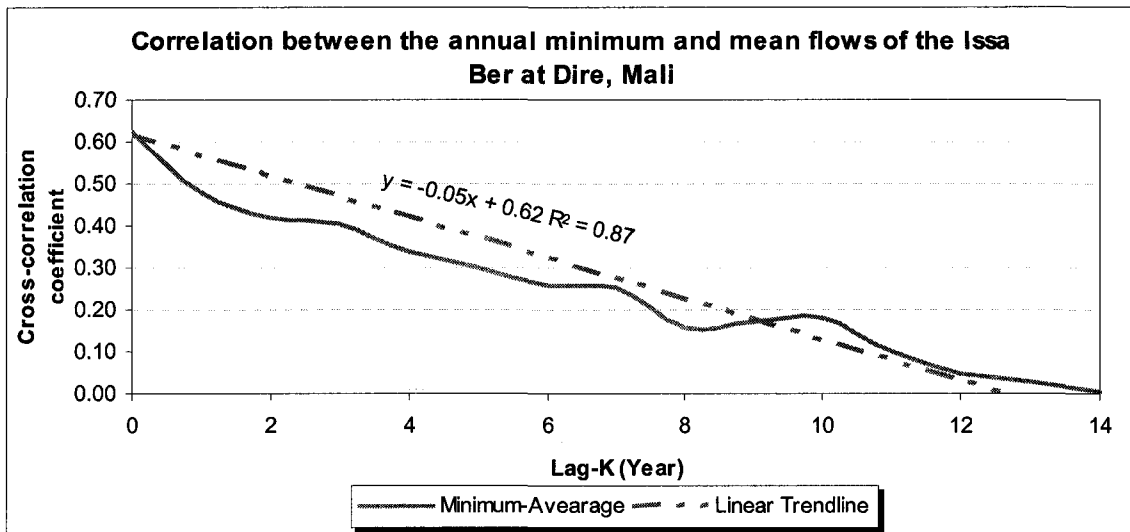


Figure A-2.4.2-2: Cross-correlation of flows of the Issa Ber at Dire, Mali