

2012

Risk Management In Reservoir Operations In The Context Of Undefined Competitive Consumption

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RISK MANAGEMENT IN RESERVOIR OPERATIONS IN THE CONTEXT OF
UNDEFINED COMPETITIVE CONSUMPTION

by

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A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Civil and Environmental Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Fall Term
2012

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ABSTRACT

Dams and reservoirs with multiple purposes require effective management to fully realize their purposes and maximize efficiency. For instance, a reservoir intended mainly for the purposes of flood control and hydropower generation may result in a system with primary objectives that conflict with each other. This is because higher hydraulic heads are required to achieve the hydropower generation objective while relatively lower reservoir levels are required to fulfill flood control objectives. Protracted imbalances between these two could increase the susceptibility of the system to risks of water shortage or flood, depending on inflow volumes and operational policy effectiveness. The magnitudes of these risks can become even more pronounced when upstream use of the river is unregulated and uncoordinated so that upstream consumptions and releases are arbitrary. As a result, safe operational practices and risk management alternatives must be structured after an improved understanding of historical and anticipated inflows, actual and speculative upstream uses, and the overall hydrology of catchments upstream of the reservoir.

One of such systems with an almost yearly occurrence of floods and shortages due to both natural and anthropogenic factors is the dual reservoir system of Kainji and Jebba in Nigeria. To analyze and manage these risks, a methodology that combines a stochastic and deterministic approach was employed. Using methods outlined by Box and Jenkins (1976), autoregressive integrated moving average (ARIMA) models were developed for forecasting Niger river inflows at Kainji reservoir based on twenty-seven-year-long historical inflow data (1970-1996). These were then validated using seven-year inflow records (1997-2003). The model with the best correlation was a seasonal multiplicative ARIMA $(2,1,1) \times (2,1,2)_{12}$ model. Supplementary

validation of this model was done with discharge rating curves developed for the inlet of the reservoir using in situ inflows and satellite altimetry data.

By comparing net inflow volumes with storage deficit, flood and shortage risk factors at the reservoir were determined based on (a) actual inflows, (b) forecasted inflows (up to 2015), and (c) simulated scenarios depicting undefined competitive upstream consumption. Calculated high-risk years matched actual flood years again suggesting the reliability of the model. Monte Carlo simulations were then used to prescribe safe outflows and storage allocations in order to reduce futuristic risk factors. The theoretical safety levels achieved indicated risk factors below threshold values and showed that this methodology is a powerful tool for estimating and managing flood and shortage risks in reservoirs with undefined competitive upstream consumption.

ACKNOWLEDGMENTS

My deepest gratitude goes first to my parents who through the years have always willingly provided me with material and moral support, the former whenever they were able, the latter always. Their encouragement throughout my educational career has been immeasurable and despite being physically away from them during my doctoral studies, I could never have achieved this without them.

I wish to thank my advisor Dr. Fidelia Nnadi for her dual role as a professional mentor and a guardian of sorts. Her timely, generous, and valuable feedback and her talent for mixing praise with constructive criticism instilled resilience in me and increased my overall motivation as a student, a teacher, a researcher and an engineer.

I am also grateful to my dissertation committee: Dr. Wang, Dr. Rowney, Dr. Divo, and Dr. Chopra for making out time out of their busy schedules to provide advice and sit on my PhD proposal and final defense committees.

Special thanks go to my friends and siblings for their encouragement and their prescriptions of the twin panaceas of “faith and patience”.

TABLE OF CONTENTS

LIST OF FIGURES	xi
LIST OF TABLES	xvi
CHAPTER 1: INTRODUCTION	1
1.1 Risk Management Considerations.....	2
1.2 Shortage Risk Consideration.	3
1.3 Flood Risk Consideration.....	4
1.4 Flood risks and innovations in reservoir operations and monitoring	6
1.5 Problem Statement and Objective of Research.	7
1.6 Goals and Objectives.....	8
1.6.1 Goal	8
1.6.2 Objectives.....	8
CHAPTER 2: ANALYSIS OF RIVER DISCHARGE AND HYDROLOGICAL	
CLASSIFICATION OF RIVER BASIN CATCHMENTS	10
2.1 Introduction.	10
2.2 Background and Study Area	11
2.2.1 The Niger River Basin.....	11
2.2.2 Kainji Reservoir and Jebba Reservoirs	14
2.3 Water Management at the Kainji reservoir	22
2.3.1 Overall Reservoir Management	22
2.3.2 Flood Events.....	23
2.4 Methodology and Data Collection	25

2.4.1	Stream discharge	25
2.4.2	Water Level Measurement	26
2.4.3	Pre-modeling considerations	27
2.5	Results and Discussion.....	29
2.6	Conclusions	34
CHAPTER 3: STOCHASTIC MODELING OF RESERVOIR INFLOWS		36
3.1	Introduction	36
3.2	Background and Data Collection	37
3.2.1	Previous Case Studies	37
3.3	Preliminary Considerations for Time Series Modeling of Inflows	40
3.4	Climate Change Considerations	41
3.4.1	Stochastic Methods and Time Series Modeling.....	42
3.5	Fundamentals of Box and Jenkins Modeling	43
3.6	Methodology	45
3.6.1	Seasonal Multiplicative Model.....	46
3.6.2	Diagnostic Checking	48
3.6.3	The Ljung–Box test.....	48
3.7	Results and Discussion.....	49
3.7.1	Actual vs. predicted inflow volume from ARIMA (1,0,1)x(0,1,1) ₁₂ model..	49
3.7.2	Actual vs. predicted inflow volume from ARIMA (1,1,1)x(2,1,2) ₁₂ model..	52
3.7.3	Actual vs. predicted inflow volume from ARIMA (2,1,1)x(2,1,2) ₁₂ model..	55
3.7.4	Jebba Reservoir Inflow Modeling	61
3.8	Conclusions	63

CHAPTER 4: VALIDATION OF RESERVOIR ALTIMETRIC LEVELS AND INFLOW

RATING CURVES.....	65
4.1 Introduction	65
4.2 Background of Satellite Altimeters and Kainji Reservoir.....	67
4.2.1 Previous Case Study: Lake Kivu Satellite-measured water level validation	70
4.3 Experimental Details and Methodology.....	72
4.3.1 Study Area.....	72
4.3.2 Data Collection.....	74
4.3.3 Temporal Correction and Alignment	76
4.3.4 Data Validation Technique.....	77
4.3.5 Spatial Correction.....	78
4.3.6 Alternative Validation of Forecasts of Reservoir Inflow	79
4.4 Results and Discussion.....	81
4.4.1 Time Series Plots of Lake Levels.....	81
4.4.2 Interannual Validation Results.....	83
4.4.3 Seasonal Validation Results	84
4.4.4 Comparison of reservoir inflows from ARIMA forecasts and rating curve.	88
4.5 Conclusions	89

CHAPTER 5: RESEROIR STORAGE VARIATIONS FROM HYDROLOGICAL MASS

BALANCE AND SATELLITE RADAR ALTIMETRY.....	91
5.1 Introduction	91
5.2 Background	92
5.3 Methodology	93

5.3.1	Data Collection.....	93
5.3.2	Reservoir Level Validation	97
5.3.3	Lake Storage from Hydrological Mass Balance	99
5.4	Results	102
5.4.1	Reservoir level validation results	102
5.4.2	Reservoir storage results	102
5.5	Conclusion.....	105
CHAPTER 6: ANALYSIS AND ESTIMATION OF FLOOD AND SHORTAGE RISKS		107
6.1	Introduction and Background.....	107
6.2	Methodology	110
6.2.1	Determination of Flood Risks	110
6.2.2	Determination of Shortage Risk Factor.....	113
6.2.3	Flow duration curve	114
6.2.4	Exceedance probability	115
6.2.5	Model with Futuristic Upstream Consumption Patterns	115
6.2.6	Examples of hypothetical reservoir inflow scenarios initially considered..	116
6.3	Results and Discussion.....	119
6.3.1	Flood risks from actual inflows.....	119
6.3.2	Flood risk factors from forecasted and hypothetical inflow scenarios.....	123
6.3.3	Shortage risk factors from actual inflows	125
6.3.4	Shortage risk factors from forecasted and hypothetical inflow scenarios...	126
6.3.5	Flow duration and exceedance probability.....	127
6.3.6	Probability Distribution of Inflows	130

6.4	Conclusions	131
CHAPTER 7: REDUCTION AND MANAGEMENT OF RISKS		133
7.1	Introduction	133
7.2	Background and Data Collection	134
7.3	Methodology	135
7.3.1	Criteria for prescribing reservoir releases and storage allocation	135
7.3.2	Steps for reducing flood and shortage risks.	136
7.4	Monte Carlo Simulation of Undefined Competitive Consumptions	137
7.5	Results and Discussion.....	138
7.5.1	Various simulated storage allocations and reservoir release scenarios for flood and shortage risk management	138
7.6	Conclusions	145
CHAPTER 8: RESEARCH SUMMARY AND FUTURE IMPLICATIONS		147
8.1	Long term implications and possible future research.....	147
8.2	Final Conclusion	148
REFERENCES		149

LIST OF FIGURES

Figure 1: Depiction of flood and drought in a small reservoir based on relative inflow changes (Schanze 2004)	3
Figure 2: Niger River originating from Guinea and terminating in Nigeria's Niger Delta (FAO report, 1996)	12
Figure 3: Kainji and Jebba reservoirs in Nigeria. (Encarta Encyclopedia).....	14
Figure 4: Kainji and Jebba Reservoirs along the Niger River (Source: Google Maps).....	16
Figure 5: Kainji Dam Site, Nigeria (Source: Google Earth).....	18
Figure 6: Kainji Dam Embankment Wall	19
Figure 7: Releases from Kainji Dam	20
Figure 8: Jebba Dam, Nigeria (Source: Google Earth).....	20
Figure 9: Niger River Basin.....	24
Figure 10: Image showing dams and flow gage location along the Niger River (Red pushpins: Dams; Green pushpins: Main flow gage stations	26
Figure 11: Schematic illustrating the effect of one river catchment hydrology on the next assuming n number of catchments.....	28
Figure 12: Comparison of Historical Inflows of Niger River headwaters with Lower Catchment	30
Figure 13: Comparison of Historical Inflows of Niger River headwaters with Middle Catchment	30
Figure 14: Comparison of Historical Inflows of Niger River headwaters with Upper Catchment.	31
Figure 15: Historical Inflows along Niger River Catchments and Flow Stations	31

Figure 16: Comparison of Historical Discharge of Niger River through Various Periods.....	32
Figure 17: Comparison of Mean Decadal Discharge Along Niger River.....	33
Figure 18: Heuristic model of Risk of Depletion of Supply at the Colorado River (Rajagoplan et al., 2009).	38
Figure 19: Time series model of the Iller River (Robinson and Rohde, 1976)	39
Figure 20: Inflow prediction at the Sewa hydroelectric Project Stage-II (Sharma et al., 2011)...	40
Figure 21: Steps in a Typical Process of Model Selection (Box and Jenkins, 1970)	45
Figure 22: Time Series of actual vs. predicted inflow volume from ARIMA (1,0,1)x(0,1,1) ₁₂ model.	49
Figure 23: ARIMA (1,0,1)x(0,1,1) ₁₂ model summary	50
Figure 24: Actual vs. predicted inflow volume ARIMA (1,0,1)x(0,1,1) ₁₂ model. ($R^2 = 0.86$).....	50
Figure 25: ACF and PACFs of ARIMA (1,0,1)x(0,1,1) ₁₂ model.....	51
Figure 26: Time series of actual vs. predicted inflow volume from ARIMA (1,1,1)x(2,1,2) ₁₂ model	53
Figure 27: Actual vs. predicted inflow volume from ARIMA (1,1,1)x(2,1,2) ₁₂ model. ($R^2 = 0.86$)	53
Figure 28: Summary of ARIMA (1,1,1)x(2,1,2) ₁₂ model	53
Figure 29: ACF and PACFs of ARIMA (1,1,1)x(2,1,2) ₁₂ model.....	54
Figure 30: Time series of actual vs. predicted inflow volume from ARIMA (2,1,1)x(2,1,2) ₁₂ model	56
Figure 31: Summary of ARIMA (2,1,1)x(2,1,2) ₁₂ model	56
Figure 32: Actual vs. predicted inflow volume from ARIMA ARIMA (2,1,1)x(2,1,2) ₁₂ model. ($R^2=0.87$)	56

Figure 33: ACF and PACFs of ARIMA (2,1,1)x(2,1,2) ₁₂ model.....	58
Figure 34: Summary of all ARIMA models.	61
Figure 35: Time series comparison of Actual and Forecasted Inflows at the Jebba Reservoir	62
Figure 36: ACF and PACF of Forecasted Inflows at the Jebba Reservoir	63
Figure 37: Altimeter Pass points over Kainji reservoir. (White Lines: ERS and ENVISAT, Red Lines: T/P and JASON-1, Olive lines: GFO. These indicate nominal ground tracks. A drift up to +/- 1km is expected in actual operation) Source: ‘Surface monitoring by satellite altimetry’	69
Figure 38: Altimetric Level Validation for Lake Kivu, Rwanda (Munyaneza, et al., 2009).....	70
Figure 39: Altimeter-Gage Comparison for Lake Kivu, Africa (Munyaneza et al., 2009).	71
Figure 40: Location of Kainji Lake (White dots: T/P satellite altimeter tracks)	73
Figure 41: TOPEX/Poseidon Global Targets (Source: European Space Agency; www.esa.int) .	75
Figure 42: ENVISAT global targets (Source: www.esa.int)	75
Figure 43: Altimeter Pass points over Kainji reservoir. (White Lines: ERS and ENVISAT, Red Lines: T/P and JASON-1, Olive lines: GFO. These indicate nominal ground tracks. A drift up to +/- 1km is expected in actual operation) Source: ‘Surface monitoring by satellite altimetry’	78
Figure 44: Envisat satellite altimeter tracks over Kainji reservoir inlet	80
Figure 45: Time series plot of gage and ERS/ENVISAT altimeter lake surface elevation.	82
Figure 46: Time series plot of gage and altimeter lake water heights.	82
Figure 47: Interannual comparison of Kainji Lake height variations: T/P altimeter vs. gage.....	83
Figure 48: Interannual comparison of Kainji Lake height variations: ERS/ENVISAT altimeter vs. gage.....	83

Figure 49: Kainji Lake height variations in dry season: T/P vs. gage	84
Figure 50: Kainji Lake height variations in wet season: T/P vs. gage.....	85
Figure 51: Kainji Lake height variations in dry season: ERS/ENVISAT vs. gage	85
Figure 52: Kainji Lake height variations in wet season: ERS/ENVISAT vs. gage.....	86
Figure 53: Discharge rating curve for reservoir inlet.....	88
Figure 54: Time series of actual, estimated, and predicted inflows.....	89
Figure 55: Kainji Reservoir Inflow.....	94
Figure 56: Kainji Reservoir Outflow.	95
Figure 57: Precipitation over Kainji reservoir.	96
Figure 58: Reservoir Evaporation.....	97
Figure 59: Image of the Kainji reservoir showing main hydrological variables	101
Figure 60: Time series of Kainji reservoir storage derived from in situ, T/P, and ENVISAT levels.....	103
Figure 61: Kainji Reservoir Level-Storage Curve	104
Figure 62: In situ storage vs. T/P-derived storage.	104
Figure 63: In situ vs. ENVISAT-derived storage	104
Figure 64: Approximate locations of some dams shown in Table 14.....	109
Figure 65: Flood risk factors for actual and forecasted inflow volumes.	120
Figure 66: Kainji reservoir flood risk factors (1984-2015).	121
Figure 67: Flood risk factors for various inflow scenarios.	124
Figure 68: Time series of shortage risk factors and inflows.....	125
Figure 69: Projected Shortage Risks.....	127
Figure 70: Flow duration curves for Kainji reservoir.	129

Figure 71: Inflow time series for Kainji reservoir.	129
Figure 72: Normal distribution of reservoir inflows.....	130
Figure 73: Lognormal distribution of reservoir inflows.	131
Figure 74: Reservoir storage prescriptions for risk management (Example result of simulation set 1)	138
Figure 75: Reservoir storage prescriptions for risk management (Example result of simulation set 2)	139
Figure 76: Reservoir storage prescriptions for risk management (Example result of simulation set 3)	139
Figure 77: Reservoir outflow prescriptions for risk management	141
Figure 78: Forecasted inflow compared with outflow situations.....	141
Figure 79: Reduction in projected flood risk factors	142
Figure 80: Statistical summary of reduced flood risk factors	143
Figure 81: Reduction in shortage risks from forecasted and hypothetical inflow scenarios.	143
Figure 82: Statistical summary of reduced shortage risk factors	145

LIST OF TABLES

Table 1: Niger River Basin Catchments and their characteristics (Zwarts et al., 2005).....	13
Table 2: Characteristics of Kainji Reservoir.....	17
Table 3: Characteristics of Jebba Reservoir.....	17
Table 4: Classified Catchments and their Annual Inflow Volumes	34
Table 5: Actual vs. predicted inflow volumes from ARIMA (1,0,1)x(0,1,1) ₁₂ model	52
Table 6: Actual vs. predicted inflow volumes from ARIMA (1,1,1)x(2,1,2) ₁₂ model	55
Table 7: Actual vs. predicted inflow volumes from ARIMA (2,1,1)x(2,1,2) ₁₂ model	59
Table 8: Actual vs. all predicted inflow volumes from ARIMA models.....	60
Table 9: Summary of Results of Altimeter-Gage Comparison for Lake Kivu, Africa. (Munyaneza et al., 2009)	71
Table 10: Characteristics of Kainji Reservoir.....	73
Table 11: Summary of datasets used	79
Table 12: Summary of Validation Results.....	87
Table 13: Comparison of altimetry-derived storage and in situ storage	105
Table 14: Existing and planned structures along the Niger River.	109
Table 15: Niger River diversions and other uses (Source: Hydroconsult, Office Du Niger 2006)	110
Table 16: List of all hypothetical consumption and release scenarios.....	118
Table 17: Empirical basis of flood risk factor calculation: Reported vs. Calculated (Source: NIWA Internal Report, 2010).....	122
Table 18: Empirical basis of flood risk factor calculation	123
Table 19: Statistical summary of flood risk factors for various inflow scenarios	124

Table 20: Official shortage years compared with shortage years from this study	126
Table 21: Statistical summary of shortage risk factors for various inflow scenarios	127
Table 22: Statistical summary of reduced flood risk factors.	142
Table 23: Statistical summary of reduced shortage risk factors.	144

CHAPTER 1:

INTRODUCTION

When hydroelectric dams and reservoirs form the focus of a nation's reliance for flood control, hydropower, and irrigation, it becomes imperative to adopt a reliable method of quantifying and managing water in the reservoirs for these purposes. The risks which seasonal inflow, storage, and outflow pose to reservoir operations must also be assessed. In cases where multiple dams exist along the length of the same river, the operational and hydrological characteristics of downstream reservoirs are inevitably influenced by dams and reservoirs upstream (Olukanni and Salami, 2012). The tasks involved in trying to fully evaluate the uncertainty involved in such systems can go beyond just scientific and socio-political measures (Staschus and Stedinger 1995). Previous works have considered multi-reservoir systems as subsets of such complex hydrological relationships between dams but not all have been entirely scientifically based (Loucks et al. 1981).

However, physical distance, topography, differing hydrology, separate water management districts and jurisdictions, and reservoir use policies make such relationships even more complex to describe within the framework of every important variable. Where only water policies and their comparisons are to be made, the presence of a central agency can make this task easier. For example, Rajabi et al. (1999) considered the problem of managing a water supply system with independent policy actions. Some work has also been done on other systems with coordinated management. Loucks et al. (1981) provided an approach to developing operating rules and considered the optimal operation of systems with multiple objectives. In addition, Haimes (1977)

developed a hierarchical model for a system composed of interacting subsystems. Each subsystem had its own objectives and constraints. However, a higher level coordinator with a system-wide objective function was needed to resolve conflicts amongst the subsystems.

1.1 Risk Management Considerations.

Risk analysis and management in reservoir operations cuts across multiple engineering sub-disciplines and can attract many definitions. To start with a broad descriptive concept of the term, the Oxford English dictionary defines risk as “a situation that could be dangerous or have a bad result”; and as “the chance or probability of something going wrong”. Therefore, risks to reservoir operations can mean any situation that could adversely affect proper or desired functionality of the operation of the reservoir. From a purely engineering perspective, this can imply structural defects, settlement, leakage, internal erosion overtopping, etc (Nedeco 1961). However, for reasons of specificity, reservoir operation risks - from a water resources perspective and within the framework of this study - is used to mean the chance of flooding arising from acutely high rates of inflow and/or precipitation. Conversely, it also refers to the propensity for water shortage to the extent that can negatively impact a reservoir’s water supply and hydropower generation potential. These two clear categories are discussed in the next two sections.

Schanze (2004) also described the interplay between flood and drought risks in a reservoir and depicted these as shown in Figure 1. It shows the propensity for flood or droughts based on relative increases in inflow factors for a hypothetical natural water basin.

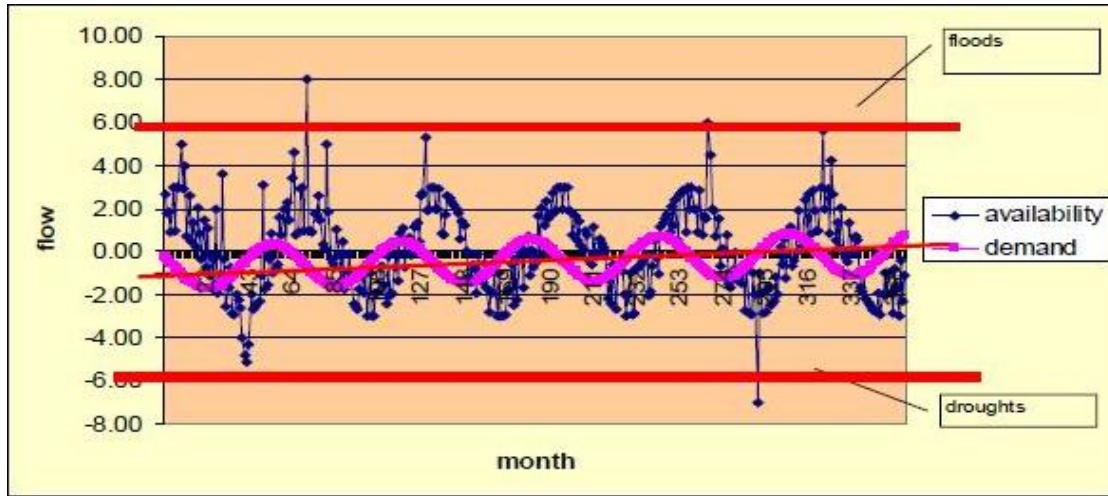


Figure 1: Depiction of flood and drought in a small reservoir based on relative inflow changes (Schanze 2004)

1.2 Shortage Risk Consideration.

In climates where precipitation and groundwater recharge fluctuate over years or decades, this can have a noticeable effect on runoff volume in the area. While this is often the case in arid areas, there exist some catchments around the globe where short-term precipitation rates have no significant relationship with stream flow within the same catchment and through the same period (Liebe et al. 2005). An example of this is the eastern half of the Inner Delta of the Niger River basin in Africa (Diallo et al. 2005). In such cases, extensive upstream effects like human activities or evaporation may impact stream flow in patterns that are distinct from the effect of precipitation or even groundwater recharge.

However, when there is a marked seasonal or annual depletion in the supply source of a reservoir, the results could be a corresponding decrease in inflow volume and consequently

availability of water for various uses like hydropower and irrigation. Shortage that results in this way can push the limits of reservoirs. This may also be evaluated using a conventional method by calculating firm yield. Firm yield is the maximum yearly demand which the reservoir can meet using only withdrawals. This demand must occur in the normal duration of such analysis and also during drought conditions. At a catchment level or local level, firm yield calculations for a reservoir are usually included in planning assessments to help estimate expected availability.

1.3 Flood Risk Consideration.

In technical literature, the term management, just like risk defined above, is expressed in more than two ways. One of these ways involves the inclusion of risk analysis while the other leaves out risk analysis. A preliminary concept is founded upon the hydrological reliability of existing flood prevention measures. In this sense, management is expressed as decisions and actions performed to reduce or lessen the remaining risk beyond flood protection design standards and how much risk remains may then be evaluated by scientific research. Developing an overall effective flood risk management techniques in this context would mean first performing flood risk analysis and then, subsequently, devising measures for flood risk management (Marsalek, 1999; Oumeraci, 2004; Hooijer et al., 2004).

The second concept defines management as sets of decisions and actions undertaken in order to analyze, evaluate and possibly reduce flood risks. Portrayed like this, flood risk management covers three phases namely risk analysis, risk assessment and risk reduction (Sayers et al., 2002).

These two concepts are actual completely divergent, provide two different options and do not necessarily have to be applied together.

Flood risk management usually starts in the form of a decision-making process and development of important considerations. During the continuous risk management process, different modes of management can be identified: the pre-flood, the actual flood event for flood management (Rosenthal and Hart, 1998), and the post-flood modes. These terms have also been introduced elsewhere to simplify the systematization of flood risk reduction activities (Kundzewicz and Samuels, 1997). According to the comprehensive understanding of flood risk management, the modes also extend to risk analysis and risk assessment.

Sayers (2002) gave the following steps in the process towards flood risk mitigation:

1. Risk Analysis
2. Risk Assessment
3. Risk Reduction

In this study, we have modified this approach by re-defining the term “risk” to mean both the likelihood of shortage of water needed to adequately meet the reservoir’s design purposes and/or the likelihood of excess water enough to cause flooding. This integral concept of dual risk was then re-configured into a single framework that includes the following steps:

1. Risk identification
2. Risk definition
3. Risk evaluation
4. Risk mitigation (or management).

1.4 Flood risks and innovations in reservoir operations and monitoring

Flooding in the catchment around some reservoirs can be a persistent problem, especially with climate variability. In effect, while an appreciable understanding of the flow patterns each river basin is critical, proper quantification of inflow volume reaching and passing through each location along the river is important as well as a clear idea about the seasonality in the inflow volumes so quantified (Liebe et al., 2005). Daily and monthly stream flow data for a given catchment area can provide some information about the net effect of the hydrological cycle of the preceding catchment area since precipitation, evaporation, runoff, and natural inflow all occur within one catchment to result in the observed stream flow into the next catchment. However, where a reservoir is involved, correct storage quantification is necessary and this can present a problem. To properly understand flood risks in reservoirs, a supplementary method for verification of storage and inflow volume calculations can be adopted for use in this study to serve as a basis for comparison. For example, data on inflow volumes and storage variations in reservoir both of which are needed to properly evaluate risks may not be readily available or may not be up-to-date. Sometimes storage-stage and area-stage curves, where available for a given reservoir, can be extremely useful estimation tools (Magome et al., 2003). But first, stage must be readily obtainable and reliable. Conventional technologies for monitoring stage and discharge typically provide water managers with ample foundational water quantity information. But in most of Africa where some technologies and policies already exist but are hampered by maintenance and implementation respectively, a supplementary solution is desired. In order for such a solution to be admissible as a water resources management tool, it must be cost-effective, able to replace conventional technologies, require little human supervision, must not be subject

to administrative barriers or political interference, and must be demonstrably reliable over long periods and in all kinds of weather. Satellite radar altimeters, devices used for remotely measuring water surface heights from space, hold the key. Their applications have been demonstrated in coastal waters and oceans, but they have also seen some successful use in inland waters (Cretaux & Birkett, 2006). The water level variations measured with this technology, if validated, can then be used complementarily with in situ measurements of both stream and reservoir levels and discharge to help understand the hydrology of the catchment where the river and reservoir are located. Reservoir storage variations may then be calculated and inflows predicted using any one of a variety of forecasting techniques available. The information derived thus can then be applied to water budget planning and strategic risk management by water managers.

1.5 Problem Statement and Objective of Research.

The title of this dissertation is:

“Risk Management in Reservoir Operations in the Context of Undefined Competitive Consumption.”

In summary, this dissertation seeks to improve water balance and strategic risk management by developing a reliable stochastic model for forecasting inflows from the lower Niger River into the Kainji and Jebba reservoirs. The model will then be used to analyze, calculate, and mitigate risks that arise from changes in real-time and futuristic competitive upstream uses. These risks involve (i) flood risks due from high inflows and high releases (ii) water shortage due to low inflows.

By analyzing historical reservoir inflow data and discharge at various upstream points, a better understanding of the effects of upstream consumption on reservoir inflow and the effects of inflow on reservoir operations risk will be gained. Then by forecasting seasonal and interannual stream flow into the Kainji reservoir, the monthly inflow volumes and the corresponding magnitudes of flood risk and shortage risks can be estimated. The methodology used and the results gathered both stand to count as immense contributions to integrated water resources management by redefining the concepts of risks in reservoir operation, assigning simplistic formulae for calculating flood risks and scarcity risks, and computing long-term reservoir storage allocation based on inflow forecasts. In river basins without a central manager or coordinated monitoring system, this technique can be applied to assess the risks associated with reservoir operation within the context of undefined competitive consumption either upstream or around the immediate catchment area.

1.6 Goals and Objectives

1.6.1 Goal

The goal of this research is to improve water balance and strategic risk management in the Kainji reservoir.

1.6.2 Objectives

This dissertation is divided into six main parts or objectives. Each one represents a set of tasks completed systematically to accomplish the overall research goal. In essence, the objectives each represent an intended or already published journal paper complete with its own introduction,

background, methodology, results, and conclusion. Together, they collectively represent the series of steps undertaken to bring this dissertation to completion. They are:

1. Classification of catchments along river basin using average historical inflow volumes to test stationarity and seasonality of inflows.
2. Selecting, testing and validation of several stochastic models for use in forecasting reservoir inflow volumes
3. Validation of satellite-measured reservoir levels for later use in developing stage-discharge curves and comparison with inflow prediction models
4. Calculation of reservoir storage (using hydrological mass balance and satellite radar altimetry) for use in risk factor estimation
5. Determination of flood and shortage risk factors based on:
 - a. actual inflows
 - b. forecasted inflows
 - c. hypothetical inflow scenarios simulating upstream uses
6. Risk management using Monte Carlo-prescribed storage allocations and controlled releases.

CHAPTER 2:

ANALYSIS OF RIVER DISCHARGE AND HYDROLOGICAL CLASSIFICATION OF RIVER BASIN CATCHMENTS

This chapter has been written into a journal article to be submitted to: *River Research and Applications* with the following title:

Salami Y. and Nnadi F., “Catchment classification in Niger River Basin based on stream discharge patterns and inflow volumes”.

2.1 Introduction.

The hydrology of the Niger River in Africa has been of immense hydrological significance to the countries Mali, Niger, and Nigeria which constitute the basin through which it runs. But water consumption patterns in the last five decades and changing interactions between catchment hydrology and stream flow have created the need for a reevaluation (Descroix et al., 2002). The occurrence of drought over the past 50 years has also greatly affected the hydrology of the river basin (Lebel et al., 2009). The flows recorded at several flow gage stations, each located in a different catchment along the river's length, from Mali to Nigeria have been recorded since the 1950s, and tied to rainfall patterns in some catchments (Andersen, et al. 2005). An overall assessment of the entire basin close to the main stream and a classification of the inflow patterns across each basin could provide helpful hydrological information for scientific and social research purposes. Flows in the upper Niger River mostly corresponded to rainfall near the headwaters in Mali. Further downstream in Nigeria, the flow goes up by over 300%. This is due to the effect of the merger with the river Benue tributary. The river annually accumulates about

80% of its flow in Nigeria, and the remaining 20% in the other countries. This necessitates studies by stakeholders on how best to maximize the benefits of the river in other countries and provide as much hydrological information in the next few decades.

Consumption patterns include reservoir and dam withdrawals, agricultural use, municipal consumption, and hydrological losses. Based on hydrological characteristics derived from inflow volumes alone, attempts have often been made to subdivide the catchments of the river based on common hydrological characteristics (Zwarts, et al. and Andersen et al., 2005). This trend has remained remarkably constant for the last five decades. Unless additional dams are planned along the river basin (which may have only minimal to negligible effects on the overall inflows), the inflow volumes at adjoining stations can easily substitute for those at successive stations, because of negligible effects in consumption patterns. The reduction in the average yearly streamflow in the Niger River has been shown to correspond to rainfall decrease, but streamflow reduction has occurred at a more substantial rate than rainfall reduction especially in the last 40 years (Andersen, et al. 2005 and Lebel et al., 2003). Identical patterns were observed in some of its tributaries (Le Barbé et al., 1993 and Mahé et al., 2000).

2.2 Background and Study Area

2.2.1 The Niger River Basin

The Niger River basin is among the largest river basins in Africa. The total length of the river is about 4,200 km. The river basin of the Niger covers 7.5% of the continent and spreads over ten countries. Rising in Guinea, the river flows northeast into Mali. East of Timbuktu, it bends to the southeast (see Figure 2), flowing across western Niger and forming part of the international

boundary between Niger and Benin. From there, the Niger enters Nigeria and flows predominantly south, finally entering the Atlantic Ocean through an extensive delta.



Figure 2: Niger River originating from Guinea and terminating in Nigeria's Niger Delta (FAO report, 1996)

Most of the Niger River basin is located in Mali (25.5 %) and Niger (24.8 %) as shown in Table 1. The area of the Niger River basin in Guinea and Ivory Coast together only slightly exceeds 5% of the total area of the basin. However, the sources of the Niger River situated in these countries and their catchments at these locations are important for the basin. The amount of water entering Mali from Guinea and Ivory Coast (i.e. about 40 km³/yr) is actually more than the quantity of water entering Nigeria from Niger (i.e. 36 km³/yr), about 1800 km further downstream (Andersen, et al., 2005). This reduction is due to, among several other reasons, the enormous

decline in runoff in the Inner Delta in Mali through evaporation combined with absence of runoff from the left bank in Mali and Niger (the Sahara desert region).

Table 1: Niger River basin catchments and their characteristics (Zwarts et al., 2005).

Country	Total area of the country (km ²)	Area of the country within the basin (km ²)	As % of total area of basin	As % of total area of country	Average annual rainfall in the basin area		
					min.	max.	mean
Guinea	245 857	96 880	4.3	39.4	1240	2180	1635
Ivory Coast	322 462	23 770	1.0	7.4	1316	1615	1466
Mali	1 240 190	578 850	25.5	46.7	45	1500	440
Burkina Faso	274 000	76 621	3.4	28.0	370	1280	655
Algeria	2 381 740	193 449	8.5	8.1	0	140	20
Benin	112 620	46 384	2.0	41.2	735	1255	1055
Niger	1 267 000	564 211	24.8	44.5	0	880	280
Chad	1 284 000	20 339	0.9	1.6	865	1195	975
Cameroon	475 440	89 249	3.9	18.8	830	2365	1330
Nigeria	923 770	584 193	25.7	63.2	535	2845	1185
Niger basin		2 273 946	100.0				

The Niger River enters Mali through various tributaries from Guinea. The main tributary, the Bani, originates from Ivory Coast and SW Mali. The overall catchment area of the Bani (129,000 km²) is nearly as large as the rest of the Upper Niger basin upstream of the Inner Niger Delta (147,000 km²) (Diallo et al., 2005). After a steep increase in flow due to high precipitation in Guinea, Ivory Coast and southwestern Mali, reaching values in the order of 1100m³/s at Koulikoro, the flow across the Inner Delta undergoes a gradual decrease in flow rate. The river experiences a drop in a part of its potential flow between Ségou, at 1000 km from its source,

Besides climate and natural seasonal variations, other factors responsible for decreases in discharge levels of Upper Niger River include dams and reservoirs, other losses, and groundwater.

2.2.2 Kainji Reservoir and Jebba Reservoirs

The Kainji and Jebba dams in Nigeria (See Figure 3, Figure 4, Figure 5 and Figure 8) constitute a dual reservoir system where the outflow from the larger feeder dam - the Kainji dam – forms the main inflow to the Jebba dam.

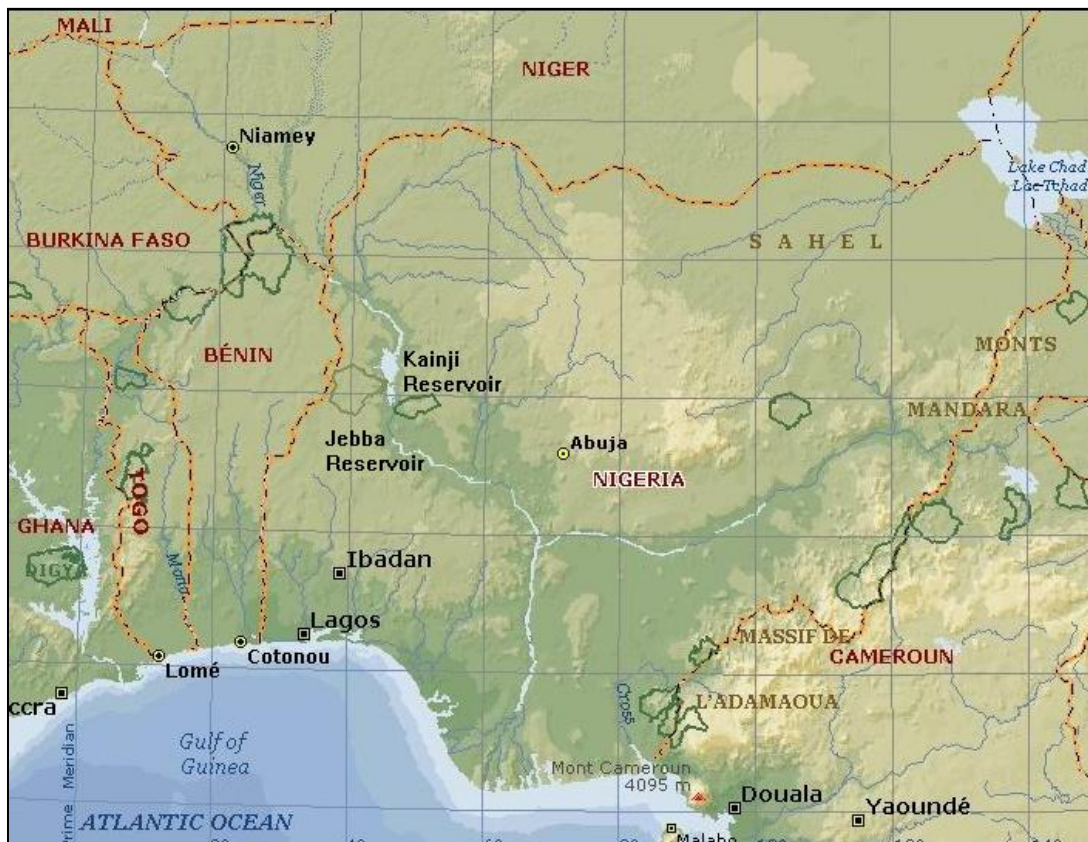


Figure 3: Kainji and Jebba reservoirs in Nigeria. (Encarta Encyclopedia)

The Kainji Lake is one of several lakes in Nigeria. It is located between latitudes 9°50' N and 10°35'N and longitudes 4°26'E and 4°40'E. It was created by impounding the Niger River in 1968 during the construction of Kainji dam, Nigeria's main hydroelectric dam. The reservoir stretches about 84 miles long and measures about 29 miles at its widest point. It covers an estimated surface area of 1270 km² and has a capacity of 15 x 10⁹ m³. The maximum water surface elevation is 141.9 m. Its live storage is about 11.5 km³ and its dead storage is about 3.5 km³ (www.kainjihydroelectricplc.org). The Kainji reservoir depends mainly on inflow from the Niger River for sustenance of the country's electricity demands, as runoff from its catchment accounts for less than 10% of inflow (Onemayin, 2008). Kainji reservoir is part of a multi-reservoir system, the other being Jebba reservoir located downstream of the Kainji dam. Both are primarily used for power generation.



Figure 4: Kainji and Jebba Reservoirs along the Niger River (Source: Google Maps).

The Jebba reservoir, located about 50 miles downstream of the Kainji reservoir, receives the outflow from the Kainji reservoir as its main inflow. It has a capacity of about 3.9 km^3 and a maximum water surface elevation of 103 m (m.a.s.l.). It was formed by the Jebba dam between 1981 and 1983. Full operation began in 1984. The reservoir is located on latitude $9^{\circ} 08' \text{ N}$ and longitude $4^{\circ} 49' \text{ E}$. The reservoir has a surface area of 270 km^2 and about 100 km long, with a width varying from 2 to 5 km. It is capable of storing 3.9 km^3 of water at elevation of 103 m above sea level, with a live storage of 1.0 km^3 . The characteristics of both reservoirs are summarized in Table 2 and Table 3.

Table 2: Characteristics of Kainji Reservoir.

Characteristics of Kainji Reservoir.	
Latitude	9°50' N
Longitude	4°40'E
Maximum Capacity (m ³)	15 x 10 ⁹
Minimum Capacity (m ³)	3.5 x 10 ⁹
Surface Area (km ²)	1270
Length (km)	135
Maximum Width (km)	30
Maximum Elevation (m.a.s.l.)	141.9

Table 3: Characteristics of Jebba Reservoir

Characteristics of Jebba Reservoir	
.Latitude	9°08' N
Longitude	4°49'E
Maximum Capacity (m ³)	3.9 x 10 ⁹
Surface Area (km ²)	270
Length (km)	100
Maximum Elevation (m.a.s.l.)	103

Kainji dam is one of the longest dams in the world. Its saddle dam closes off a tributary valley. The majority of the dam's structure is made from earth, but the center section, which contains the hydroelectric turbines, was made out of concrete. This section is 65 m (215 ft) high. The dam was intended to have a power generating capacity of 960 Megawatts. But because only eight of its twelve turbines have been installed, the generating capacity of the dam has been reduced to 760 Megawatts. The dam generates electricity for Nigeria's major cities and some of the electricity is exported to the neighboring country of Niger (www.kainjihydroelectricplc.org).



Figure 5: Kainji Dam Site, Nigeria (Source: Google Earth)

In addition, droughts have reduced the inflow and made the Niger's water flow unpredictable, further straining the dam's power output capacity. The dam has a single-lock chamber capable of lifting barges 49 m (160 ft). Kainji Lake measures about 135 km (about 84 mi) long and about 30

km (about 19 mi) at its widest point, and supplies a local fishing industry. In 1999 uncoordinated opening of floodgates led to local flooding of about 60 communities and more than \$100 million in damages. The creation of the reservoir necessitated the resettlement of more than 40,000 mostly rural people (Olawepo, 2008) and the construction of new villages for the resettled locals.



Figure 6: Kainji Dam Embankment Wall



Figure 7: Releases from Kainji Dam



Figure 8: Jebba Dam, Nigeria (Source: Google Earth)

Usually, low inflows occur in dry season by which time the reservoir is almost filled from the past rainy season (Oyebande,1995). These high water levels are gradually lowered over the next few months (December to May) in the form of use for power generation until the following season of high precipitation and inflows (July to November). The reservoir level at this stage is low and can cater to flood control requirements over the next few months. However, flooding of the area is still almost a yearly phenomenon. This is because although filling of the reservoir is expected to be over by October from the ‘White floods’ caused by high precipitation in the immediate lower Niger River catchment (see section 2.3.2), periods of high inflows sometimes extend late into November and December owing to the late arriving ‘Black floods’ (caused by precipitation in the upper and middle Niger River catchments) and uncoordinated reservoir releases in upstream catchments (Abiodun, 1973; and Oyebande, 1995). These late high inflows overwhelm the storage capability of the Kainji dam causing sudden high releases by Kainji reservoir operators in order to prevent damage to the dam and maintain safe water levels.

In what is an assumption of identical hydrological behavior for two consecutive years, Kainji dam operators have always typically adopted the operational policies of one year for the next year (Onemayin, 2008) A proof of the flaw associated with this practice is the yearly flooding and loss of lives and property because some drought years have been followed unexpectedly by flood years. The inaccuracy involved in applying the operational policies of the preceding year to the current year arises from the inherent difficulty in forecasting inflows to the reservoir. Research on various water uses and other consumption patterns along the Niger River is very limited. Also, the very distinct climates even between adjoining countries can mean widely distinct evaporation, precipitation and seepage patterns, and consequently, usually wide

variations in inflow volumes at different catchments. A forecast of inflows then is necessary to understand the potential risks from high or low inflow volumes and ‘White’ and ‘Black’ floods (discussed in Section 2.3.2). But first, an understanding of the river’s hydrology and different upstream uses must be gained. As a result, a need arises for an exhaustive analysis of upstream dams consumption and release patterns. The purpose of this study is to proffer methods by which the inflow of the Niger River into the Kainji reservoir may be forecasted so that flood risks and shortage risks can be estimated and adequately catered for. Because the reliability of flow forecasts depend strongly upon the hydrology of the river, of the upstream catchments, and the various consumption patterns along the river, it is important to understand the hydrology of the area, historical flows, and the processes involved in streamflow forecasting.

2.3 Water Management at the Kainji reservoir

2.3.1 Overall Reservoir Management

Kainji dam has suffered from both natural and man-made issues, that range from extreme flood and drought events, poor administration and management, low inflows from the Niger River, social issues arising from poorly resettled displaced people, political interference, and disrepair of equipment (Olawepo, 1998). No robust water management scheme currently exists apart from those used since the 1970s and 1980s since the construction of the Kainji dam. Most improvement and overhauls are targeted more towards repairing old equipment than replacement with current technology. Operational policies are sometimes adequate but characteristically low inflows from the Niger River in some years cause low natural storages and impact negatively on hydroelectricity generation capacity (www.kainjihydroelectricplc.org).

2.3.2 Flood Events

Flooding downstream of the Kainji catchment is a yearly occurrence both due to naturally high inflows and human-induced factors like arbitrary releases from upstream catchments. In the lower Niger River downstream of Kainji and Jebba dams, streamflow is largely determined by the reservoir operation policies of both hydroelectric power schemes and catchment runoff. Reservoir outflow from the larger upstream dam (Kainji) forms the main inflow to the smaller downstream dam (Jebba). Excess discharge from the Kainji dam therefore often results in flooding of the catchment downstream after both reservoirs are filled. These high releases occur mainly because the operators typically adopt the operational policies of one year for the next year (Onemayin, 2008).

The flood regimes are of two types:

1. 'White floods'

The name arises from the color of the water which is heavily laden with milky white sandy sediments due to the silt it carries. This occurs annually in the rainy season (July to November). It is caused by high stream inflows arising from precipitation in the immediate Lower Niger River catchment where the Kainji reservoir is located. Its maximum discharge is about 2500 m³/s. (FAO, 1996). It begins around July/August and reaches its peak in September/October. To prevent damage to the dam, the authorities increase releases which cause unintended flooding downstream. (Oyebande, 1995).

2. 'Black Floods'.

This results from runoff from the upper and middle catchments of the Niger River. This runoff travels as far as 2700 km before reaching Nigeria over four months later peaking at about 2000 m³/s. The water from the upper catchment is known for its comparative clarity by the time it reaches Nigeria (see Figure 9) because most of the silt it carries has been deposited in swampy areas. Thus it is called the 'black flood'. It reaches the Kainji reservoir in January/February at its peak with a discharge of about 2000 m³/s which then decreases to lower than 100 m³/s in May–June at the peak of the dry season (Andersen et al. 2005).



Figure 9: Niger River Basin

2.4 Methodology and Data Collection

2.4.1 Stream discharge

Average daily recorded discharge data for each flow station along the Niger was obtained for various time periods between 1950 and 2010. The duration of recorded discharge data varied depending on how long the flow gage station had been in operation and whether or not there were missing data due to equipment malfunction, flood damage, drought, etc. Figure 10 shows the location of these stations (in green) and the location of the major dams along the river (in red). Data for 1993 was collectively missing from each flow station dataset. These lags and their resultant extrapolation are shown on the time series plots in the results section.



Figure 10: Image showing dams and flow gage location along the Niger River (Red pushpins: Dams; Green pushpins: Main flow gage stations)

2.4.2 Water Level Measurement

Inflow and reservoir level data for the Kainji are measured in situ daily. In situ daily and monthly average reservoir levels were collected for the reservoir while altimetric levels for the river were collected at random locations along the length of the river.

2.4.3 Pre-modeling considerations

The task of modeling the hydrological behavior of the river basin intended in Chapter 4 by accounting for all hydrological parameters along the different catchment of the river must be highlighted in this chapter. It can often be simplified depending on the information and objective (Robinson & Rhode, 1976). Precipitation, evaporation, and groundwater recharge are obvious necessary inclusions where the task involves developing rigorous hydrological model of the area (Keim et al., 2004). But advances in inflow forecasting models consider the actual stream runoffs from each successive catchment. This is because the effect of precipitation, evaporation, and other significant hydrological parameters collectively result in streamflow out of a given catchment, making it possible to simplify the flow modeling process by assigning all catchment outflows as the main input variables.

$$\text{Kainji reservoir storage } S_{t=1} = S_{t=0} + [(Q_{in} - Q_{out}) \times t_{0-1} + (P - E) + G]$$

$$Q_{in(1)} = f \left[f(Q_{in}, P, E, G, W)_2 ; f(Q_{out-2}, P, E, G, W)_3 ; f(Q_{out}, P, E, G, W)_4 \dots ; f(Q_{out}, P, E, G, W)_n \right]$$

Q_{in} = river inflow to new catchment or gauge station

Q_{out} = river outflow leaving previous catchment or gauge station

P = precipitation

E = evaporation

G = groundwater recharge

W = other withdrawals, human uses, etc

n = number of catchments.

Figure 11 attempts to mimic the Niger River basin behavior where evaporation E , precipitation P , and catchment inflow all result in catchment outflow, which is equal to the discharge measured at each location along the basin.

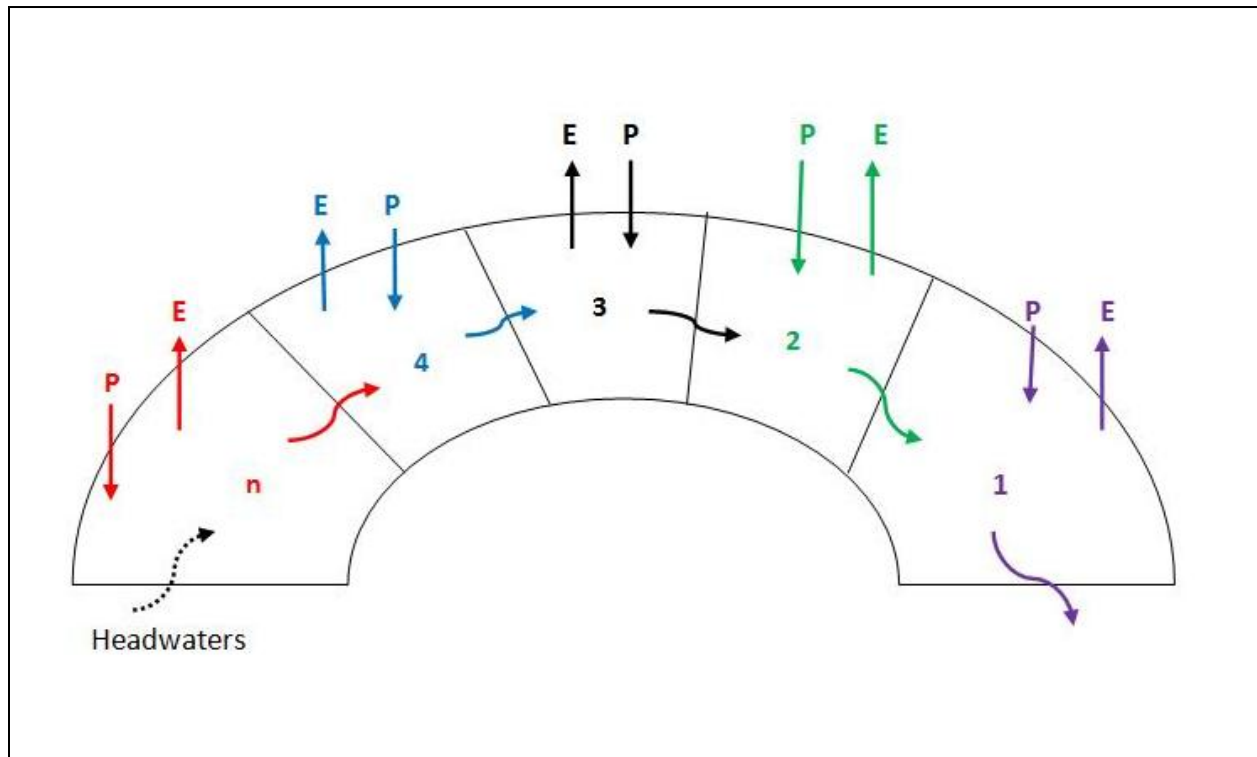


Figure 11: Schematic illustrating the effect of one river catchment hydrology on the next assuming n number of catchments

The simplified functions become:

$$\text{Storage } S_{t=1} = S_{t=0} + [(Q_{in} - Q_{out}) \times t_{0-1} + (P - E)]$$

$$Q_{in(1)} = F [f(Q_{in}2) ; f(Q_{out}3) ; f(Q_{out}4) \dots ; f(Q_{out}n)]$$

2.5 Results and Discussion

From the pre-modeling considerations in the methodology section, it can be inferred that the most significant hydrological variable for streamflow modeling is river discharge leaving each catchment. The net result of all contributions to and subtraction from each catchment result in a value equal to the discharge leaving the catchment (Figure 11).

Figure 12, Figure 13, and Figure 14 show the comparisons of headwaters inflow volumes with annual inflow volumes at the lower, middle and upper Niger River catchments respectively. The patterns follow those already explained, in which the river gains in discharge by as much as 300% as it enters the lower catchment in Nigeria. Four clearly distinct inflow categories can be observed, one for each classified catchment: the head waters, the upper catchment, the middle catchment, and the lower catchment. The values of discharge from various flow gage stations within each catchment are identical as shown in Figure 12, Figure 13, and Figure 14. These are summarized in Table 4. Figure 15 shows the comparison between all inflows stations upstream of and including the Kainji and Jebba reservoirs.

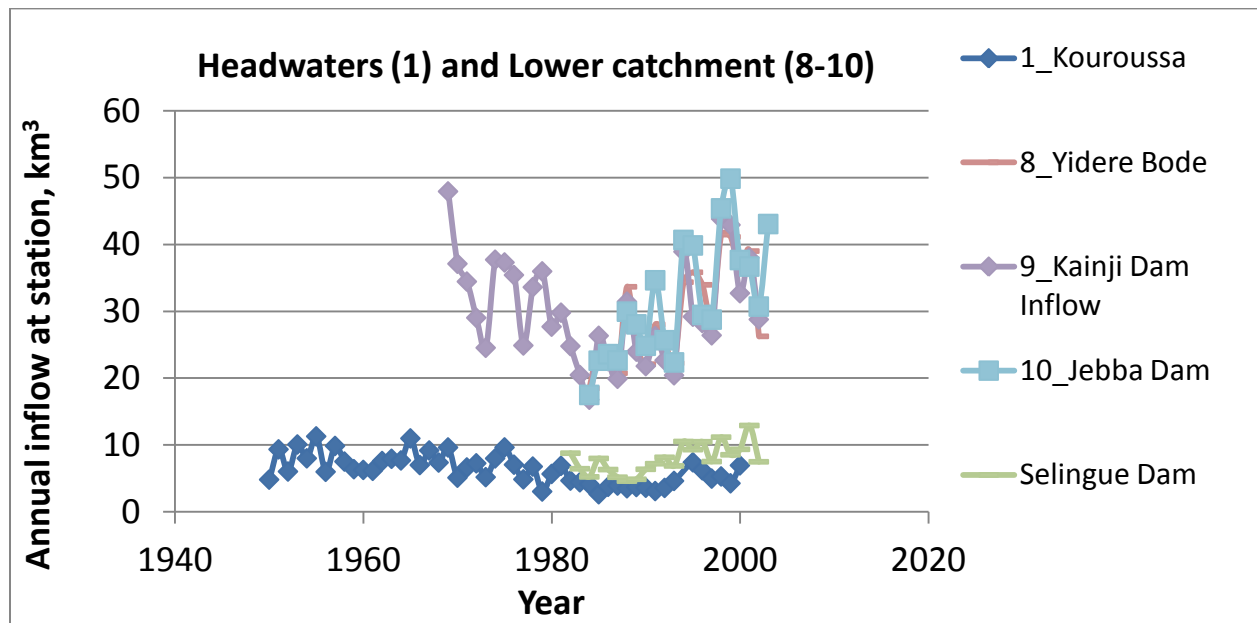


Figure 12: Comparison of Historical Inflows of Niger River headwaters with Lower Catchment

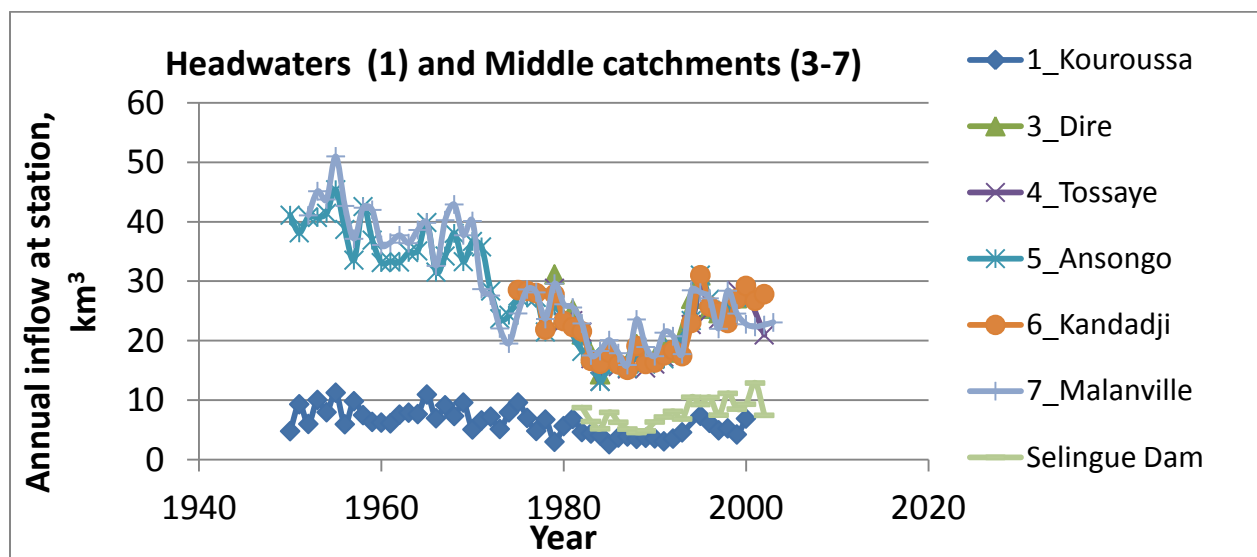


Figure 13: Comparison of Historical Inflows of Niger River headwaters with Middle Catchment

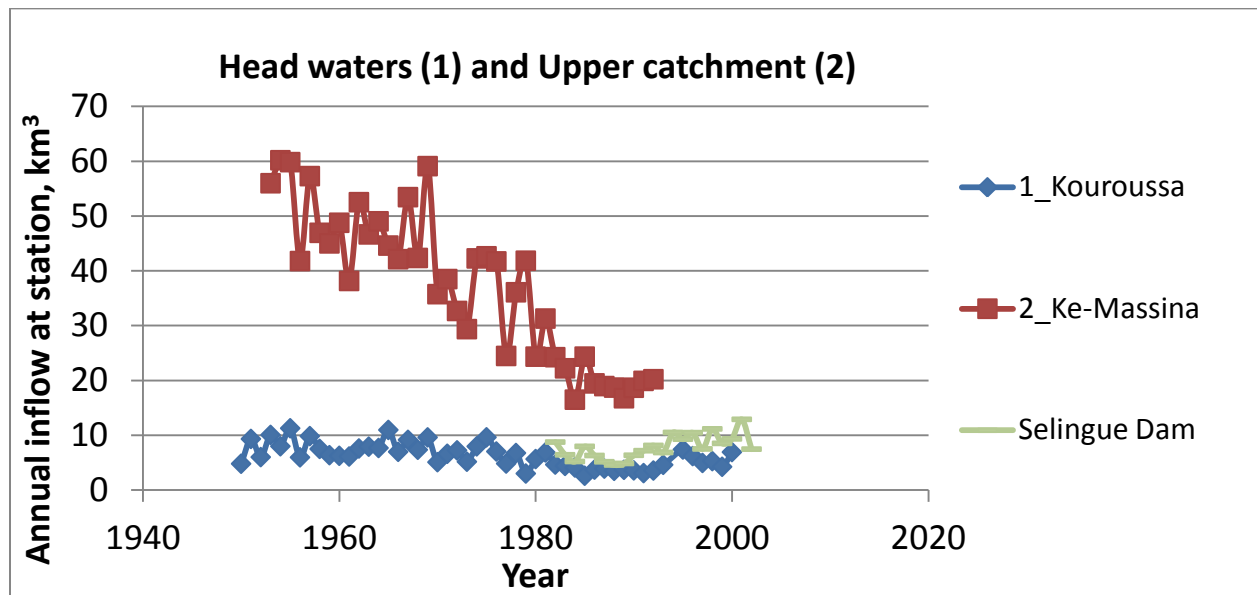


Figure 14: Comparison of Historical Inflows of Niger River headwaters with Upper Catchment.

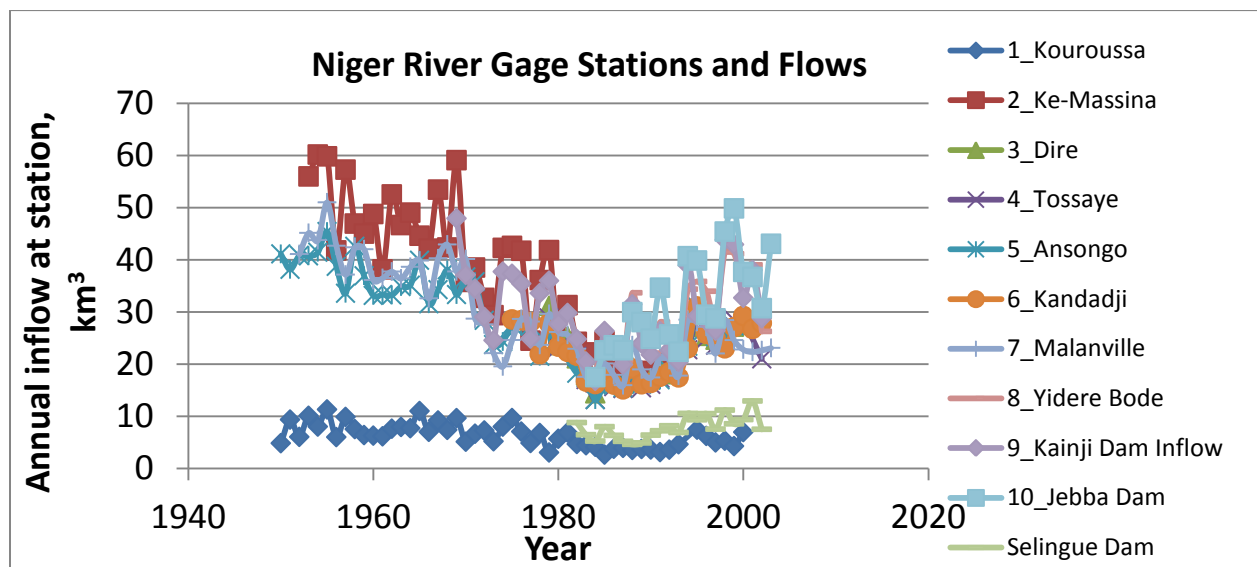


Figure 15: Historical Inflows along Niger River Catchments and Flow Stations

Figure 16 and Figure 17 reveal the mean discharge recorded at the several flow stations along the Niger River. They show that for the same station over time intervals ranging for 10 years to 50 years, very little changes in discharge have occurred. In Figure 17, the drought of the late 1970s and early 1980s are clearly reflected, especially in the downstream section of the lower Niger River. The presence of relatively little changes in stream inflow at the same points over five decades is an indication of relative stability in discharge patterns and suggests that the system is amenable to modeling for the purpose of discharge forecasting.

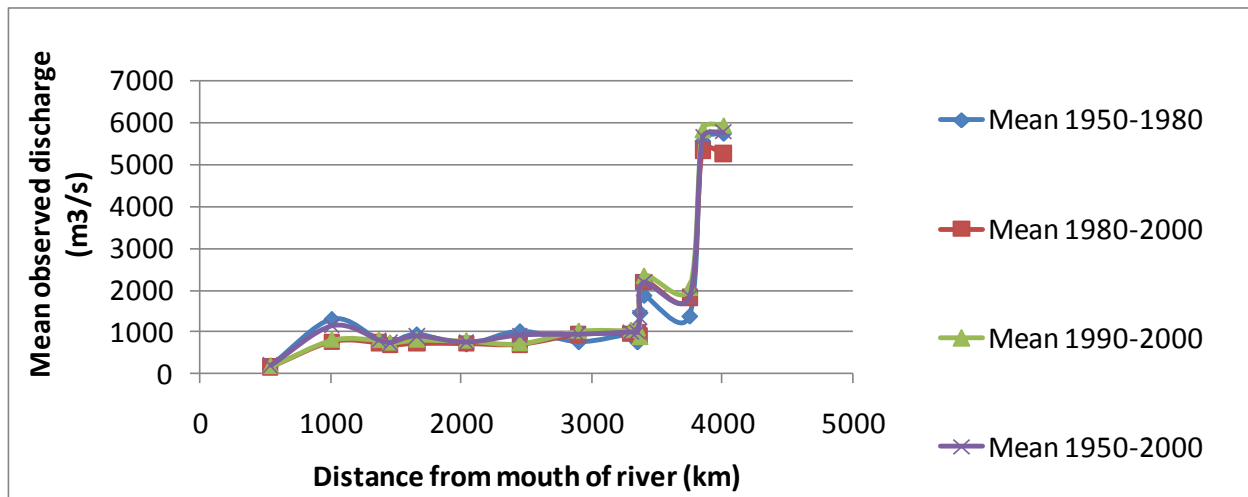


Figure 16: Comparison of Historical Discharge of Niger River through Various Periods

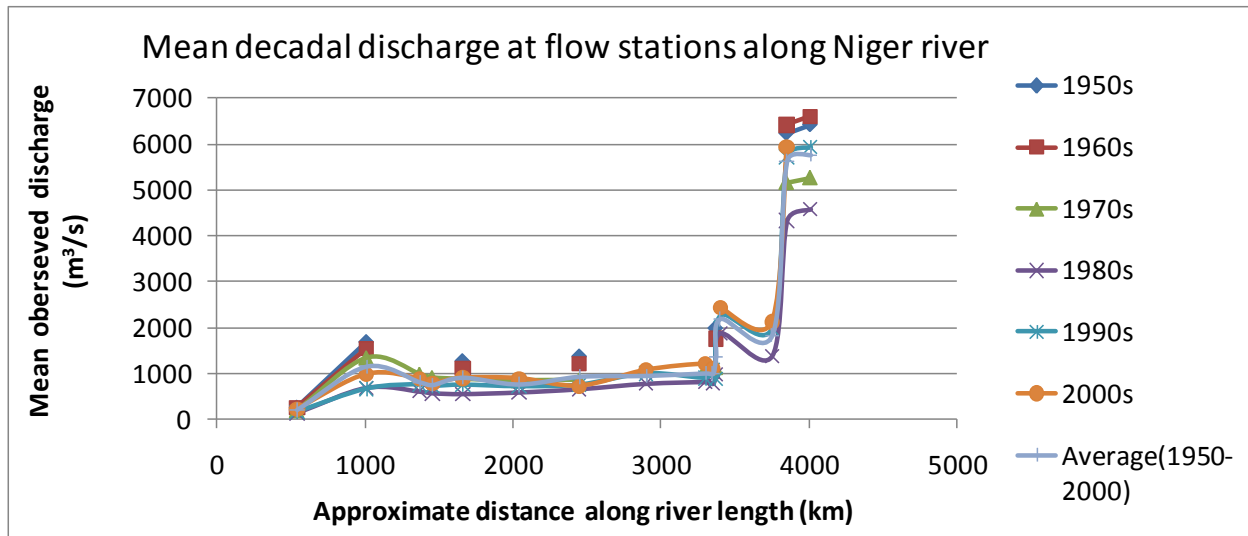


Figure 17: Comparison of Mean Decadal Discharge Along Niger River

In Table 4, the average yearly inflow volume at each station is shown. All stations along the river with identical inflow volumes over several suggest similarities in catchment hydrology. In other words, in spite of the interplay between such hydrological parameters like precipitation, evaporation, infiltration, catchment inflow and catchment outflow, the net hydrological input is the stream discharge measured at each location and the similarity in these discharges for different catchments suggests identical patterns of use and hydrological characteristics. Different colors are used to show catchments with identical inflow characteristics.

Table 4: Classified Catchments and their Annual Inflow Volumes

Gage location	Country	Max recorded Yearly volume (km ³)	Minimum recorded yearly volume (km ³)	Average volume (km ³)
Kouroussa	Guinea	9.62	2.61	5.21
Selingue dam Inflow	Mali	12.9	4.2	7.37
Ke-Massina inflow	Mali	42.66	16.49	27.07
Dire	Mali	31.16	14.38	22.07
Tossaye	Mali	29.31	13.18	21.98
Ansongo	Mali	36.71	13.15	21.91
Kandadji	Niger Rep.	31.02	15.13	22.41
Malanville	Benin/ Niger Rep	40.14	15.92	22.91
Yidere Bode	Nigeria	41.47	18.45	29.18

2.6 Conclusions

The results from this study show a high consistency in mean monthly, mean annual, and mean decadal discharge at various flow stations and catchment areas along the Niger River over 50 years. This trend makes the physical system attractive for stochastic inflow modeling and therefore should give fairly reliable forecasts over short periods. Also, the task involving classification of catchments along the Niger River revealed that inflows from eleven catchment areas spread across more than four countries and examined over a fifty-year period can be

grouped into four hydrological catchments based on very identical stream discharge values. For inflow modeling purposes, this suggests a physical system whose stream flow characteristics can be extrapolated where there are missing data or where simple hydrological calculations are desired. Overall, the relative stability of the system makes it amenable for stochastic modeling. In chapter 3, this task is performed and the results of the forecasts are compared with observed values.

CHAPTER 3:

STOCHASTIC MODELING OF RESERVOIR INFLOWS

This chapter is being written into a journal article intended for publication in: *Stochastic Hydrology and Hydraulics* under the following title:

Salami, Y. and Nnadi F., “Stochastic Prediction of Stream Inflows in a Dual Reservoir System with Multiple Release Constraints”

3.1 Introduction

Forecasting flows in rivers was one of first forecasting problems that attracted scientists and engineers. Early work in the 1940s on the River Nile flow forecast laid the foundation for much work in this area (Hurst, 1950; Bras et al., 1985) leading to the development of the Hurst coefficient which is a vital parameter for characterizing the degree of mean reversion of a time series. Correct estimation of river flows is of paramount importance to the sustenance of the inhabitants around rivers. In fact, records of water levels and flows for the River Nile date back to around 2500 B.C. leading to one of the longest recorded time series of a natural phenomenon (Atiya et al., 1999). It is useful then for studying the river flow patterns and as a benchmark time series for studying and comparing different forecasting algorithms. A study by Fleten and Kristoffersen (2008) examined short-term hydropower production planning by stochastic programming. However, they observed that day-ahead market costs and inflows to the reservoir are uncertain beyond the current operation day so that water must be allocated among the reservoirs in order to strike a balance between current profits and anticipated profits.

Most of the forecasting methods consider one-day-ahead forecast. For some other rivers, e.g. the Nile river streamflow forecasting (Atiya et al., 1999), a longer term forecast such as ten-day ahead or a month ahead may be more helpful given its long historical inflows, but then may be more complicated than the one-day ahead forecast. For this study in the Niger River in Africa, monthly time series of discharge were investigated for patterns by which futuristic inflows may be correctly predicted.

3.2 Background and Data Collection

3.2.1 Previous Case Studies

Case I:

A study on the Colorado river basin was conducted to see the risks that population growth and a changing climate will have on future reliability of the Colorado River water supply by Rajagoplan et al., (2009). Using a heuristic model, the annual risk to the Colorado River water supply for 2008–2057 was assessed. The historical flows modeled showed that projected demand growth superimposed upon historical climate variability results in only a small probability of annual reservoir depletion through 2057 (See Figure 18). In contrast, a scenario of 20% reduction in the annual Colorado River flow due to climate change by 2057 results in a near tenfold increase in the probability of annual reservoir depletion by 2057. However, the analysis suggests that flexibility in current management practices could mitigate some of the increased risk due to climate change–induced reductions in flows.

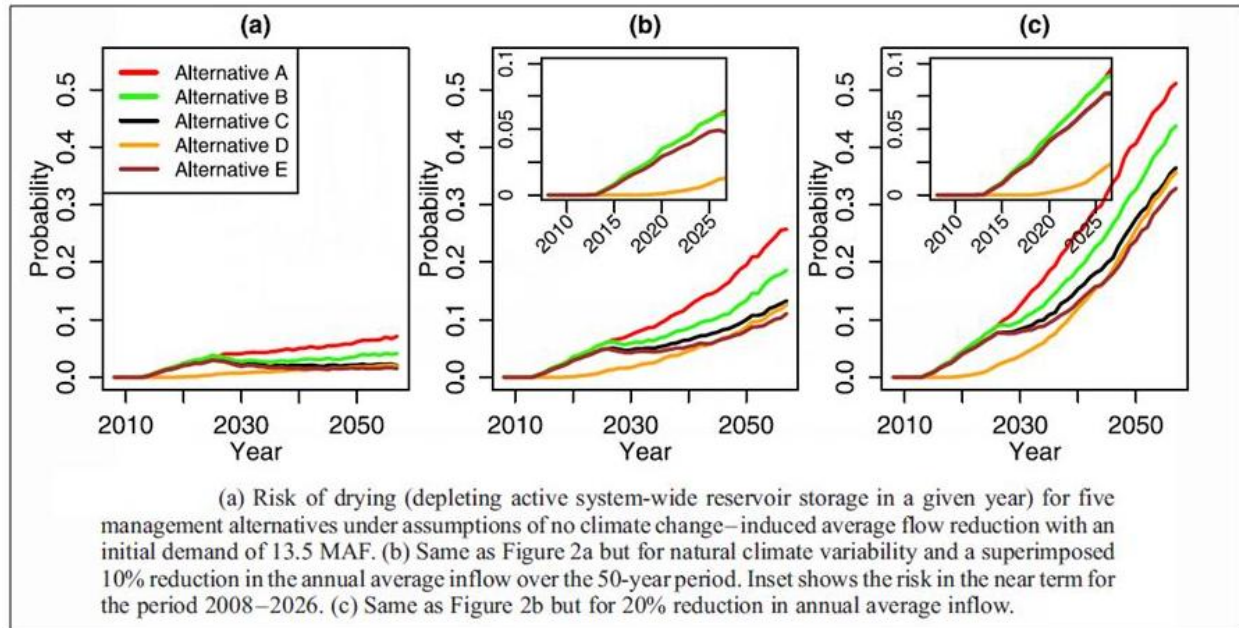


Figure 18: Heuristic model of Risk of Depletion of Supply at the Colorado River (Rajagoplan et al., 2009).

Case 2:

Robinson and Rohde (1976) applied multivariate forecasting methods to stream flows of the river Iller catchment in Germany, which is representative of some of the typical types encountered in the country. The time series structure of the streamflow was described by a set of statistical parameters from which the catchment areas can be parametrically classified and regionalized according to the physical characteristics, local climate and geographical location. Simple stochastic models, with emphasis on the seasonal multiplicative model, were considered. These models properly described the streamflow generating process and may be used for synthetic data generation for water resources planning and operational purposes. Their performance and limitations were discussed. The time series of the model is shown in Figure 19.

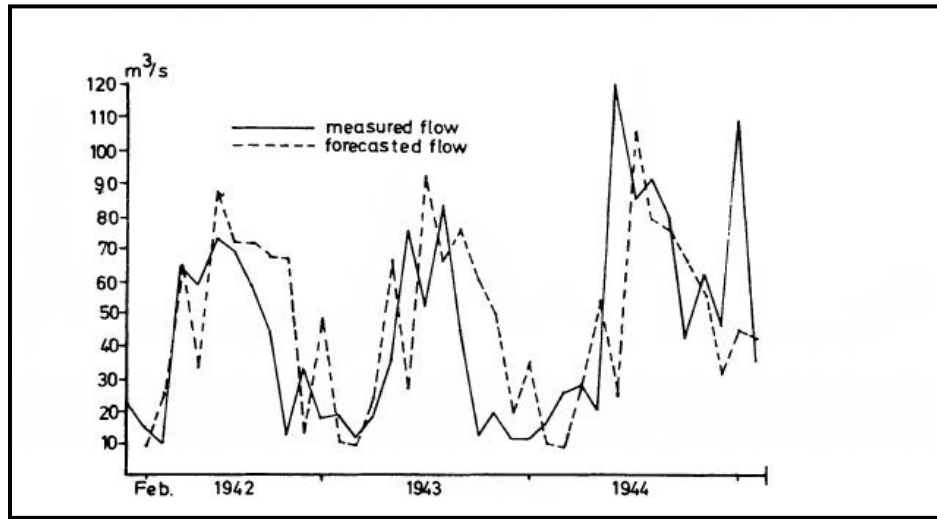


Figure 19: Time series model of the Iller River (Robinson and Rohde, 1976)

Case 3:

This study by Sharma et al. (2011) involved taking historical inflow series from Sewa hydroelectric Project Stage-II which is a run-of-the river project for model development. Sixteen years of historical inflows data of the river out of available 18 years inflow data was used and an Artificial Neural Network Model was 'trained' to predict 2 years inflows (See Figure 20). In order to accomplish this task, the historical inflow series was employed for training, validating and testing with three different proportions of neural network ratios 60:20:20, 80:10:10 and 90:05:05 were analyzed. The analysis of this study demonstrates the ability of neural network prediction model, to forecast quite accurately ten days inflows of two years ahead and generate synthetic series of ten days inflows that preserve the key statistics of the system ten days inflows. This in a way helps in effective utilization of available water resources.

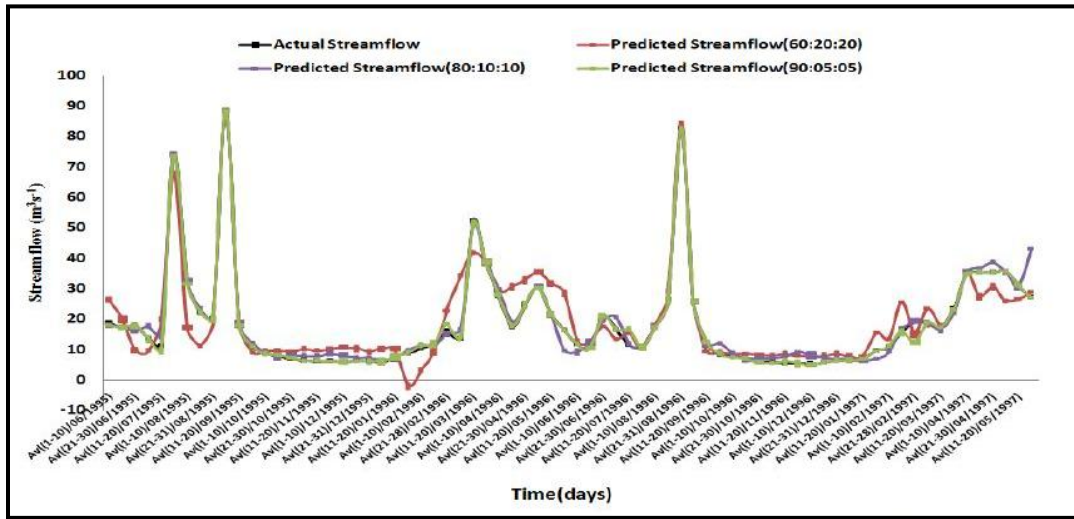


Figure 20: Inflow prediction at the Sewa hydroelectric Project Stage-II (Sharma et al., 2011)

3.3 Preliminary Considerations for Time Series Modeling of Inflows

Time series models require a deal of understanding of the fundamental techniques because of the uniqueness of each data set and modeling choice (Kall and Wallace, 1994). Extensive research studies and numerous books exist to help aid the understanding of the forecasting of water resources systems. Any attempt towards such forecasts generally considers, among other things, two important aspects:

- (1) scale of interest (i.e. temporal and/or spatial extent);
- (2) range of interest (i.e. how far into the future, at a chosen scale of interest).

Depending upon the task at hand, either of these may take priority. For instance, the scale (e.g. monthly or annual) may be more important for devising long-term water management efforts, while the range (at a chosen daily or hourly scale, for example) may become more crucial for

undertaking short-term flood risk analysis. It must be noted however that there is no such thing as “the best forecasting method” because models are only as good as the accuracy of the assumptions they are founded upon. (Chartfield and Prothero, 1973)

Makridakis and Hibon (1979) suggested after carefully evaluating and comparing results of various forecasting techniques that “Box–Jenkins has the better performance of being able to accommodate structural changes”. Naylor et. al. (1972) also stated that “Box–Jenkins results were significantly better in all cases, and they provide better forecasts by a factor of almost two to one”. Cooper and Nelson (1975) and McWhorter (1975) also corroborated these assertions. Despite the Box – Jenkins relative reliability, it should be remembered that forecasting models are to be regarded as management forecasting tools and not as completely infallible predictors of the future.

3.4 Climate Change Considerations

The argument for the inclusion or exclusion of climate change considerations in a river discharge prediction model has been discussed extensively (Arnell, 1997).

First, because significant climate change only occurs over many hundred years, a time series model for streamflow prediction for five or ten years ahead may not be seriously affected by the effect of climate (Arnell, 1997). Secondly, time series analysis of water resources systems typically depicts models that represent the behavior of a system over a long period of time. In essence, any characteristics of the system’s hydrology already include the effect, albeit long-term and minimal, of climate change. Climate change patterns, the argument contends, is already inherent in whatever model is so developed (Hipel and McLeod, 1994)

The Kainji Lake is the largest in Nigeria and one of the longest and largest in Africa by both surface area and volume. As a result, its storage variations and general hydrological behavior are important for national- and perhaps continental-scale water monitoring. The climate in the area is of mild south Sahelian climate, with precipitation averages of 1025 mm yearly. Kainji reservoir is part of a multi-reservoir system in Nigeria. Kainji is the ‘mother’ reservoir while the downstream reservoir, Jebba reservoir, is the ‘baby’ reservoir. Both lie along the Niger River in Nigeria. The Kainji and Jebba reservoirs are located close to each other so that the release from the Kainji is the main inflow to Jebba. The runoff contribution from the Kainji reservoir catchment accounts for less than 10% of the outflow from Kainji and suggests that the system can be thought of as a single reservoir with the demand for hydroelectric power generation of the lower reservoir satisfied as a downstream requirement (Onemayin, 2008). As a result, inflow and storage in both reservoirs certainly affect each other. It follows then that proper quantification of storage in the Kainji would help water budget planners in Nigeria with effective management of both reservoirs for the main uses of hydropower generation and flood control.

3.4.1 Stochastic Methods and Time Series Modeling

Common Methods

Autoregressive (AR) Models for modeling time series is the autoregressive (AR) model:

$$X_t = \delta + \phi_1 X_{t-1} + \phi_2 X_{t-2} + \dots + \phi_p X_{t-p} + A_t$$

where X_t is the time series, A_t is white noise, and $\phi_1, \phi_2, \dots, \phi_p$ = model parameters

$$\delta = (1 - \sum_{i=1}^p \phi_i) \mu$$

with μ denoting the process mean and δ is a constant (often omitted for simplicity).

An autoregressive model is simply a linear regression of the current value of the series against one or more prior values of the series. The value of p is called the order of the AR model. AR models can be analyzed with one of various methods, including standard linear least squares techniques. They also have a straightforward interpretation.

Moving Average (MA) Models

Another common approach for time series analysis is the moving average (MA) model:

$$X_t = \mu + A_t - \theta_1 A_{t-1} - \theta_2 A_{t-2} - \dots - \theta_q A_{t-q}$$

where X_t is the time series, μ is the mean of the series, A_{t-1} denote white noise, and $\theta_1, \dots, \theta_q$ are the parameters of the model. The value of q is called the order of the MA model.

That is, a moving average model is conceptually a linear regression of the current value of the series against the white noise or random shocks of one or more prior values of the series. Sometimes the autocorrelation functions (ACF) and partial autocorrelation functions (PACF) will suggest that a MA model would be a better model choice and sometimes both AR and MA terms should be used in the same model.

3.5 Fundamentals of Box and Jenkins Modeling

The Box-Jenkins autoregressive moving average (ARMA) model is a combination of the AR and MA models described previously.

$$X_t = \delta + \phi_1 X_{t-1} + \phi_2 X_{t-2} + \dots + \phi_p X_{t-p} + A_t - \theta_1 A_{t-1} - \theta_2 A_{t-2} - \dots - \theta_q A_{t-q}$$

where the terms in the equation have the same meaning as given for the AR and MA model respectively.

The Box-Jenkins model assumes that the time series is stationary. A typical model selection flowchart is shown in Figure 21. Otherwise, Box and Jenkins recommend differencing non-stationary series one or more times to achieve stationarity. Doing so produces an ARIMA model, with the "I" standing for "Integrated". Box-Jenkins models are quite flexible due to the inclusion of both autoregressive and moving average terms. Generally, an ARIMA model is typically characterized by the notation 'ARIMA (p,d,q) model', where p, d, and q refer to the orders of autoregression, integration(or differencing), and moving average respectively.

For instance: Given a time series process $\{X_t\}$, the first order AR process is denoted by ARIMA (1,0,0) or simply AR (1). For another time series process $\{A_t\}$ the first order MA process is denoted by ARIMA (0,0,1) or simply MA (1)

There are three primary stages in building a Box-Jenkins time series model.

1. Model Identification
2. Model Estimation
3. Model Validation

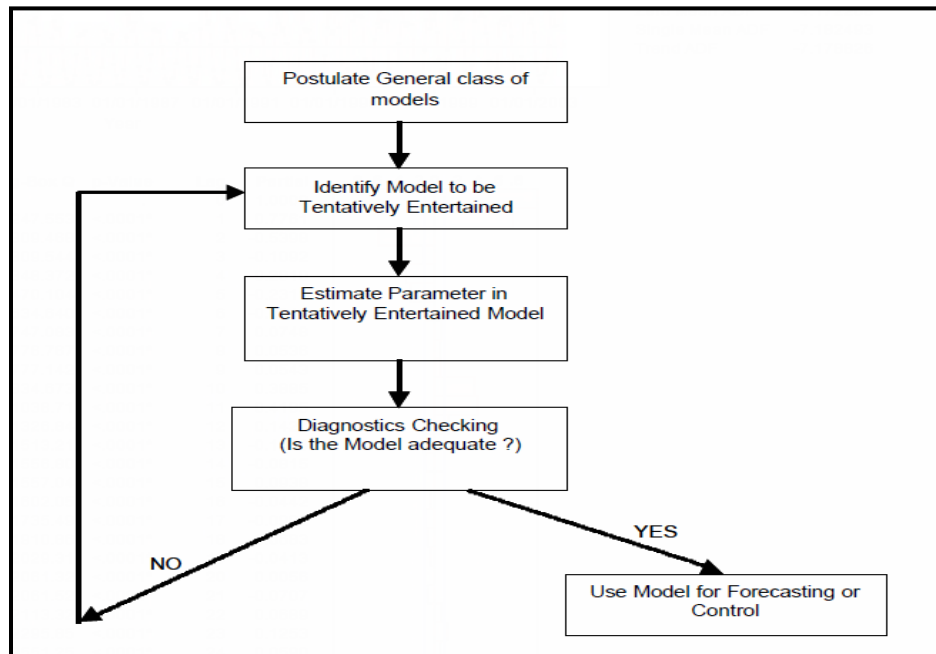


Figure 21: Steps in a Typical Process of Model Selection (Box and Jenkins, 1970)

3.6 Methodology

To fit the various time series models of inflows, a combination of both deterministic and stochastic methods was used. Ultimately, statistical computing packages (R and JMP) were employed for fitting the models and computing parameter estimates. The forecasts were then done using the model parameters so determined. Several time series models were tried using fundamental fitting methods constructed based on Box and Jenkins modeling techniques described in the Background section. First a simple autoregressive model AR (1), and then a moving average model MA(1) were tried. Next, the second order models were tried; AR (2) and MA (2) but these models were unreliable.

3.6.1 Seasonal Multiplicative Model

In the more fundamental and straightforward models earlier discussed, an underlying deterministic cycle, estimated from monthly techniques or a fitted harmonic sine function, is typically assumed (Singh et al., 2011). Basically, a seasonal ARIMA model is an ARIMA (p,d,q) model whose residuals ε_t can be further modeled by an ARIMA(P,D,Q)s structure with linear operators (P,D,Q).

In some monthly streamflow series distinct deterministic patterns may be uncertain or difficult to reliably estimate even from a long historic in situ data record (Robinson and Rohde, 1976). Data sets like reservoir water level time series would exhibit strong seasonality, more from being a seasonally controlled natural system. However, time series plots of stream discharge and inflow volume at the Kainji reservoir revealed that both seasonal and non-seasonal patterns may be present. While the inflows follow a given pattern yearly, the random presence of high inflows in some years suggested some non-seasonality which was better investigated by a different method of deseasonalizing and modeling. This was made possible by applying the differencing techniques as proposed by Box and Jenkins (1970)

Here an annual-cyclic series can be made stationary by differencing annually allowing for and a multiplicative ARIMA (p,d,q) x (P,D,Q) model fitted to the series of interest. The terms (p,d,q) and (P,D,Q) denote the orders of autoregression, differencing, and moving averages for the non-seasonal and seasonal ARIMA models respectively. Next, the procedure for finding the most appropriate multiplicative model was performed. This is basically an intensive iterative process of exploring, fitting, and comparing different models and results. So far, the best models for each task are presented along with the model parameters and results.

The operators of a seasonal ARIMA model, defined as ARIMA (p,d,q)x(P,D,Q)s, can be expressed by:

AR (p) nonseasonal operator of p order,
$$\phi(B) = 1 - \phi_1(B) - \phi_2 B^2 - \dots - \phi_p B^p ;$$

AR (P) seasonal operator of P order,
$$\phi(B) = 1 - \phi_1(B)^s - \dots - \phi_P B^{sP} ;$$

MA (q) nonseasonal operator of q order,
$$\theta(B) = 1 - \theta_1(B) - \theta_2 B^2 - \dots - \theta_q B^q$$

MA (Q) seasonal operator of Q order,
$$\theta(B) = 1 - \theta_1(B)^s - \theta_2(B)^{2s} - \dots - \theta_Q B^{Qs}$$

In every case applied for forecasting Kainji reservoir inflows, the models with the highest reliability were multiplicative ARIMA (p,d,q) x (P,D,Q) models of the variety discussed above because of the similarity in measured and simulated datasets. But none of these models worked for inflows to Jebba reservoir. According to Box and Jenkins (1970), no guidelines exist for the initial estimate values; rather various values have to be experimented. For Jebba reservoir inflows, the estimated coefficient values produced forecast errors that did not show any evidence of randomness about zero. Therefore, the model was considered unreliable and discarded. The lack of true seasonality in Jebba inflows may be responsible, given that inflow to the Jebba reservoir depends strongly on release policies at the upstream Kainji reservoir.

3.6.2 Diagnostic Checking

The next step is the diagnostic checking. This is the technique of checking the model by examining the autocorrelations of the residual. If the model is adequate, then the pattern of the autocorrelation will be independently and randomly distributed around zero. The adequacy of the Kainji inflow models is reflected in the results section. A chi-square test was also used to assist in checking whether the residual sample auto-correlations exhibit any systematic errors. A value of P (pass) was assigned to acceptable models and F (fail) to unacceptable models.

3.6.3 The Ljung–Box test

The Ljung–Box test is a statistical test the helps determine if any of a group of autocorrelations of a time series are different from zero. While it is possible to do this by testing for randomness at each distinct lag, the Ljung–Box tests the overall randomness based upon a number of lags.

The test statistic is:

$$Q = n(n+2) \sum_{k=1}^h \frac{\hat{\rho}_k^2}{n-k}$$

where n is the sample size, $\hat{\rho}_k$ is the sample autocorrelation at lag k , and h is the number of lags being tested.

For more complex models like the ARIMA (p,d,q) models which require integration of the autoregressive and moving average models, parameter estimation can be complex and makes

manual methods error prone. For some of these, statistical computing packages (R and JMP) were employed to analyze the data sets, complete iterations, and test for the most reliable model.

3.7 Results and Discussion

3.7.1 Actual vs. predicted inflow volume from ARIMA (1,0,1)x(0,1,1)₁₂ model.

For the Kainji reservoir, a time series comparison of the actual inflow volume and the forecasted inflow volume from the ARIMA model is shown in Figure 22. The ARIMA (1,0,1)x(0,1,1)₁₂ model gave a determination coefficient of 0.862, a standard deviation of 0.694, and a variance estimate of about 0.481 (See Figure 23 and Figure 24).

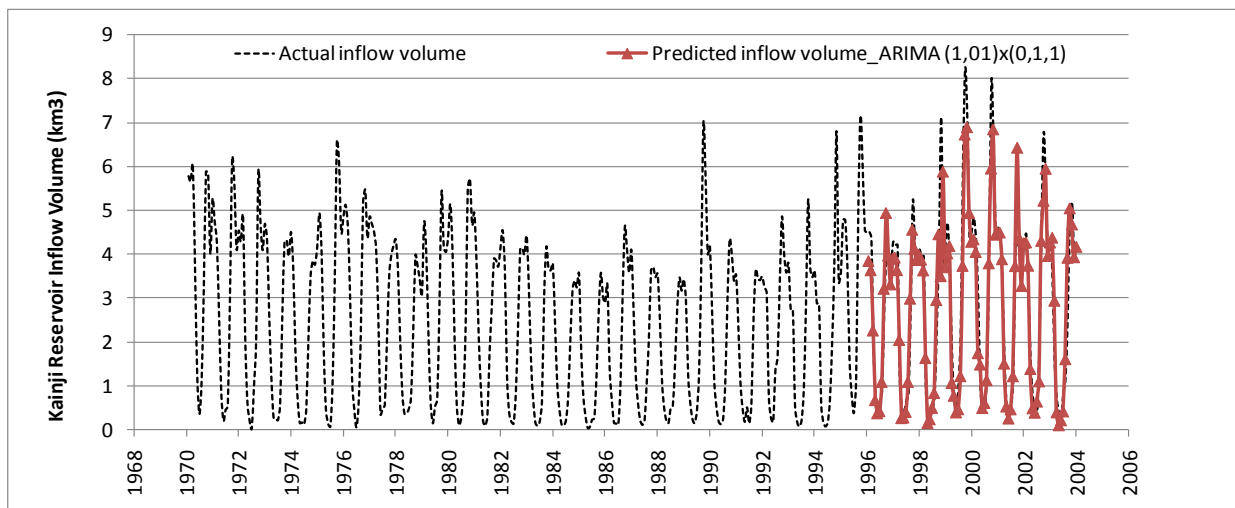


Figure 22: Time Series of actual vs. predicted inflow volume from ARIMA (1,0,1)x(0,1,1)₁₂ model.

Model Summary			
DF	387	Stable	Yes
Sum of Squared Errors	186.474698	Invertible	Yes
Variance Estimate	0.48184677		
Standard Deviation	0.69415183		
Akaike's 'A' Information Criterion	837.352444		
Schwarz's Bayesian Criterion	853.227274		
RSquare	0.86206009		
RSquare Adj	0.86099629		
MAPE	36.8213354		
MAE	0.45806414		
-2LogLikelihood	829.352444		

Figure 23: ARIMA (1,0,1)x(0,1,1)₁₂ model summary

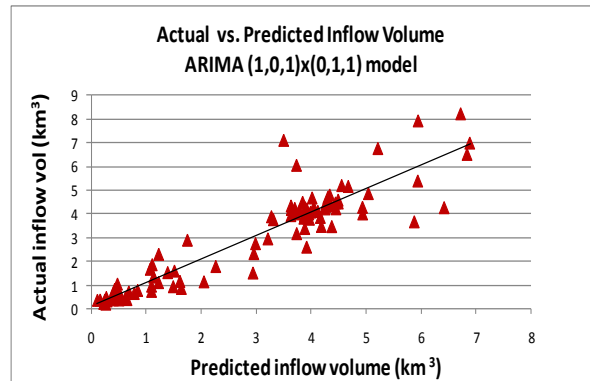


Figure 24: Actual vs. predicted inflow volume ARIMA (1,0,1)x(0,1,1)₁₂ model. ($R^2 = 0.86$)

In Figure 25, the ACF and PACF of the model both show evidence of randomness about zero. The ACF also decays to zero before the first five lags. This rapid decay to zero before the 5th lag of the ACF indicates seasonality of the series.

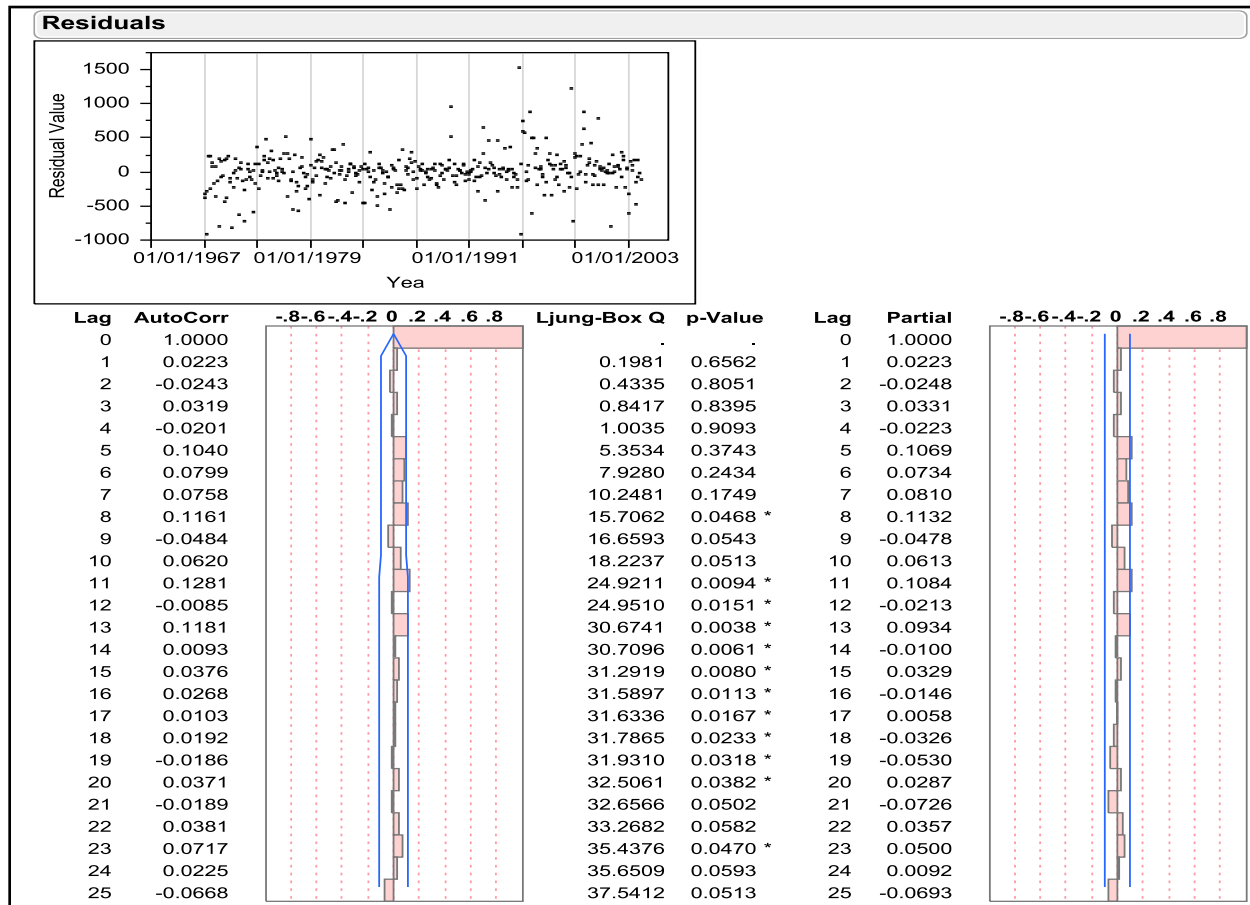


Figure 25: ACF and PACFs of ARIMA (1,0,1)x(0,1,1)₁₂ model.

Table 5 shows a two-year (2000-2001) sample of the data tested and the forecast results from the ARIMA (1,0,1)x(0,1,1)₁₂ model. A side-by-side comparison on the actual inflow volume and the predicted inflow volume is shown along with the respective upper and lower confidence limits of the results. The average relative error between forecasted inflow volume and actual inflow volume is about 15%.

Table 5: Actual vs. predicted inflow volumes from ARIMA (1,0,1)x(0,1,1)₁₂ model

Month	Actual inflow volume at Kainji dam (km3)	Predicted inflow volume at Kainji dam (km3)	Std Err Pred Volume (km3)	Residual Volume (km3)	Upper CL (0_95) Volume (km3)	Lower CL (0_95) Volume (km3)	Relative error (%)
1/1/2000	4.8184416	4.340854458	0.69415183	0.47758714	5.701367049	2.980342	9.9116516
2/1/2000	4.2892416	4.052091276	0.69415183	0.23715032	5.412603867	2.691579	5.528957
3/1/2000	2.9140992	1.748623257	0.69415183	1.16547594	3.109135848	0.388111	39.994381
4/1/2000	0.953856	1.49014553	0.69415183	-0.5362895	2.85065812	0.129633	56.223322
5/1/2000	0.3964032	0.501693282	0.69415183	-0.1052901	1.862205873	-0.85882	26.56136
6/1/2000	0.469152	0.616117133	0.69415183	-0.1469651	1.976629723	-0.7444	31.325697
7/1/2000	1.3606272	1.134159797	0.69415183	0.2264674	2.494672388	-0.22635	16.644339
8/1/2000	4.1622336	3.793655334	0.69415183	0.36857827	5.154167925	2.433143	8.8552998
9/1/2000	7.94448	5.95179996	0.69415183	1.99268004	7.312312551	4.591287	25.082574
10/1/2000	6.5326176	6.843613365	0.69415183	-0.3109958	8.204125956	5.483101	4.7606608
11/1/2000	4.48416	4.446613295	0.69415183	0.0375467	5.807125886	3.086101	0.8373186
12/1/2000	4.6041696	4.495202633	0.69415183	0.10896697	5.855715224	3.13469	2.3667018
1/1/2001	4.4836416	4.497875371	0.69415183	-0.0142338	5.858387961	3.137363	0.31746
2/1/2001	3.4086528	3.887062418	0.69415183	-0.4784096	5.247575008	2.52655	14.035152
3/1/2001	1.6123968	1.512191	0.69415183	0.1002058	2.87270359	0.151678	6.2147109
4/1/2001	0.520992	0.534871811	0.69415183	-0.0138798	1.895384402	-0.82564	2.6641121
5/1/2001	0.2196288	0.261412059	0.69415183	-0.0417833	1.621924649	-1.0991	19.02449
6/1/2001	0.508032	0.471014355	0.69415183	0.03701764	1.831526946	-0.8895	7.2864789
7/1/2001	1.1276064	1.224067664	0.69415183	-0.0964613	2.584580255	-0.13644	8.5545155
8/1/2001	4.0229568	3.731822562	0.69415183	0.29113424	5.092335153	2.37131	7.2368224
9/1/2001	4.284576	6.426179679	0.69415183	-2.1416037	7.78669227	5.065667	49.984028
10/1/2001	4.3738272	4.35689354	0.69415183	0.01693366	5.717406131	2.996381	0.3871589
11/1/2001	3.903552	3.278897555	0.69415183	0.62465445	4.639410145	1.918385	16.002206
12/1/2001	4.2345504	4.256436989	0.69415183	-0.0218866	5.61694958	2.895924	0.5168575
						Average =	15.013177

3.7.2 Actual vs. predicted inflow volume from ARIMA (1,1,1)x(2,1,2)₁₂ model.

The results of the forecast of inflow volumes at the Kainji reservoir using the ARIMA (1,0,1) (1,0,1)x(0,1,1)₁₂ are presented below. A time series comparison of the actual inflow volume and the forecasted inflow volume from the ARIMA model is shown in Figure 26. The ARIMA (1,0,1) (1,0,1)x(0,1,1)₁₂ model gave an determination coefficient of 0.863, a standard deviation of 0.693, and a variance estimate of about 0.480 as shown in Figure 27 and Figure 28. These results appear only marginally better than the results from the ARIMA (1,0,1) (1,0,1)x(0,1,1)₁₂.

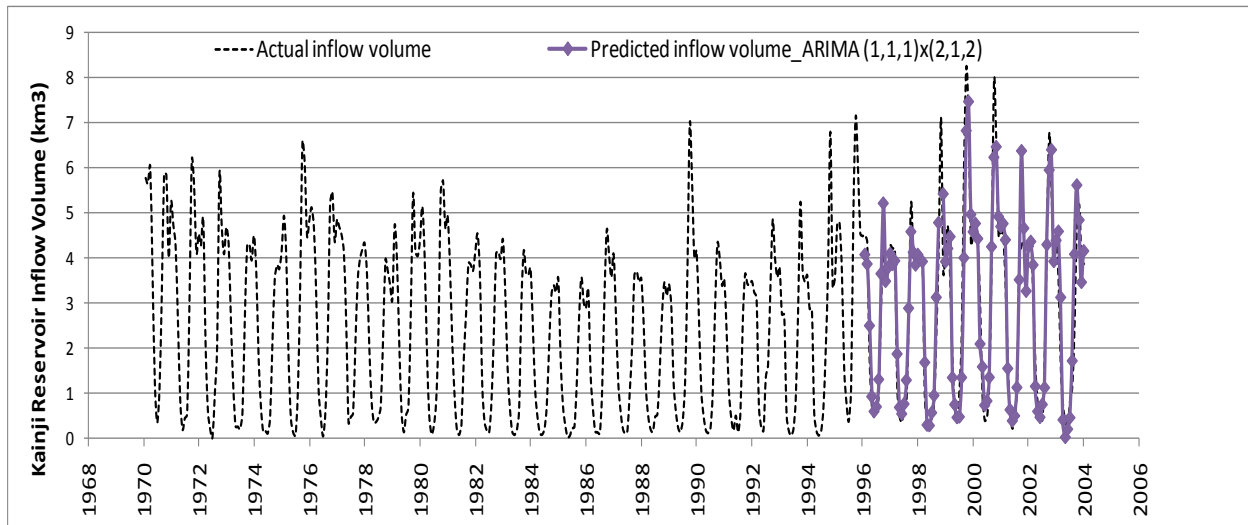


Figure 26: Time series of actual vs. predicted inflow volume from ARIMA (1,1,1)x(2,1,2)₁₂ model

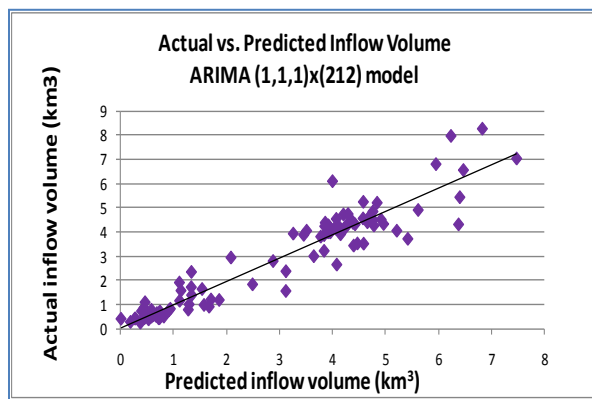


Figure 27: Actual vs. predicted inflow volume from ARIMA (1,1,1)x(2,1,2)₁₂ model. ($R^2 = 0.86$)

Model Summary			
DF	378	Stable	Yes
Sum of Squared Errors	181.786937	Invertible	Yes
Variance Estimate	0.48091782		
Standard Deviation	0.69348239		
Akaike's 'A' Information Criterion	830.520886		
Schwarz's Bayesian Criterion	858.193589		
RSquare	0.86362019		
RSquare Adj	0.86149479		
MAPE	53.0549331		
MAE	0.47069665		
-2LogLikelihood	816.520886		

Figure 28: Summary of ARIMA (1,1,1)x(2,1,2)₁₂ model

In Figure 29, the ACF and PACF of the model both show evidence of randomness about zero. As in the previous model, the ACF also decays to zero before the first five lags. This rapid decay to zero before the 5th lag of the ACF indicates seasonality of the series. The overall reliability of the

model is evidenced in the plot of coefficient of correlation (Figure 27 and Figure 28) and in Table 6 which shows relative errors.

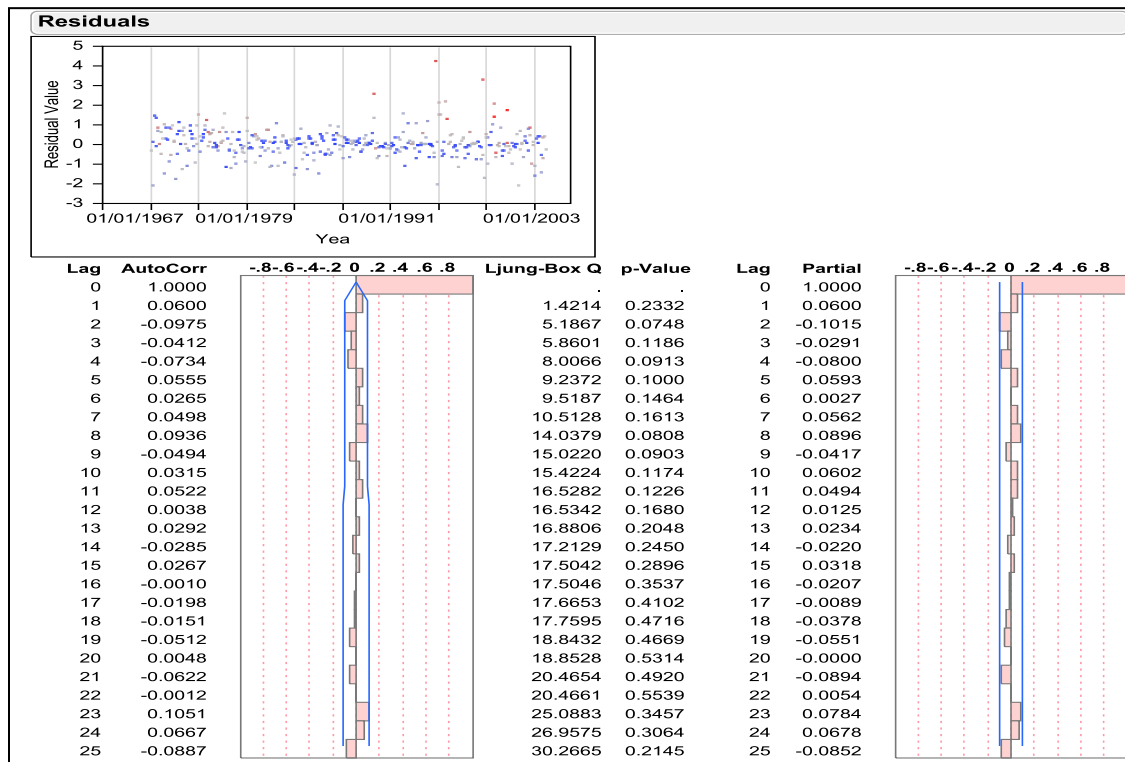


Figure 29: ACF and PACFs of ARIMA (1,1,1)x(2,1,2)₁₂ model.

In Table 6, a two-year (2000-2001) sample of the actual data used and the forecast results are shown. A side-by-side comparison on the actual inflow volume and the predicted inflow volume is shown along with the respective upper and lower confidence limits of the results. The average relative error between forecasted inflow volume and actual inflow volume is about 13.7%. This results indicate that this model is marginally better than the ARIMA (1,0,1) (1,0,1)x(0,1,1)₁₂ previously tested.

Table 6: Actual vs. predicted inflow volumes from ARIMA (1,1,1)x(2,1,2)₁₂ model

Month	Actual inflow volume at Kainji dam (km3)	Predicted inflow volume at Kainji dam (km3)	Std Err Pred Volume (km3)	Residual Volume (km3)	Upper CL (0_95) Volume (km3)	Lower CL (0_95) Volume (km3)	Relative error (%)
01/01/2000	4.8184416	4.763316182	0.69348239	0.05512542	6.122516686	3.404116	1.1440508
02/01/2000	4.2892416	4.427243163	0.69348239	-0.1380016	5.786443667	3.068043	3.2173884
03/01/2000	2.9140992	2.087439782	0.69348239	0.82665942	3.446640286	0.728239	28.36758
04/01/2000	0.953856	1.579576628	0.69348239	-0.6257206	2.938777131	0.220376	65.599066
05/01/2000	0.3964032	0.425553982	0.69348239	-0.0291508	2.084754485	-0.63365	7.353821
06/01/2000	0.469152	0.520856573	0.69348239	-0.0517046	2.180057076	-0.53834	11.020857
07/01/2000	1.3606272	1.34567862	0.69348239	0.01494858	2.704879124	-0.01352	1.0986536
08/01/2000	4.1622336	4.24756879	0.69348239	-0.0853352	5.606769294	2.888368	2.0502259
09/01/2000	7.94448	6.234514768	0.69348239	1.70996523	7.593715272	4.875314	21.523942
10/01/2000	6.5326176	6.468917263	0.69348239	0.06370034	7.828117766	5.109717	0.975112
11/01/2000	4.48416	4.91804756	0.69348239	-0.4338876	6.277248064	3.558847	9.6760053
12/01/2000	4.6041696	4.695467865	0.69348239	-0.0912983	6.054668368	3.336267	1.9829475
01/01/2001	4.4836416	4.761919228	0.69348239	-0.2782776	6.121119731	3.402719	6.2065092
02/01/2001	3.4086528	4.400355156	0.69348239	-0.9917024	5.759555659	3.041155	29.093675
03/01/2001	1.6123968	1.543169809	0.69348239	0.06922699	2.902370313	0.183969	4.2934215
04/01/2001	0.520992	0.624069518	0.69348239	-0.1030775	1.983270022	-0.73513	19.784856
05/01/2001	0.2196288	0.279572489	0.69348239	-0.0599437	1.738772992	-0.97963	27.293182
06/01/2001	0.508032	0.489608303	0.69348239	0.0184237	1.848808806	-0.86959	3.6264836
07/01/2001	1.1276064	1.11973503	0.69348239	0.00787137	2.478935533	-0.23947	0.6980601
08/01/2001	4.0229568	3.513905082	0.69348239	0.50905172	4.873105586	2.154705	12.653671
09/01/2001	4.284576	6.377920546	0.69348239	-2.0933445	7.73712105	5.01872	48.857683
10/01/2001	4.3738272	4.659359052	0.69348239	-0.2855319	6.018559555	3.300159	6.5281923
11/01/2001	3.903552	3.261743214	0.69348239	0.64180879	4.620943718	1.902543	16.441661
12/01/2001	4.2345504	4.258733676	0.69348239	-0.0241833	5.617934179	2.899533	0.5710943
						Average =	13.752422

3.7.3 Actual vs. predicted inflow volume from ARIMA (2,1,1)x(2,1,2)₁₂ model.

The results of the forecast of inflow volumes at the Kainji reservoir using the ARIMA (2,1,1)x(2,1,2)₁₂ are presented below. A time series comparison of the actual inflow volume and the forecasted inflow volume from the ARIMA model is shown in Figure 30. The ARIMA (2,1,1)x(2,1,2)₁₂ model gave a determination coefficient of about 0.87, a standard deviation of 0.69, and a variance estimate of about 0.476 as shown in Figure 31 and Figure 32.

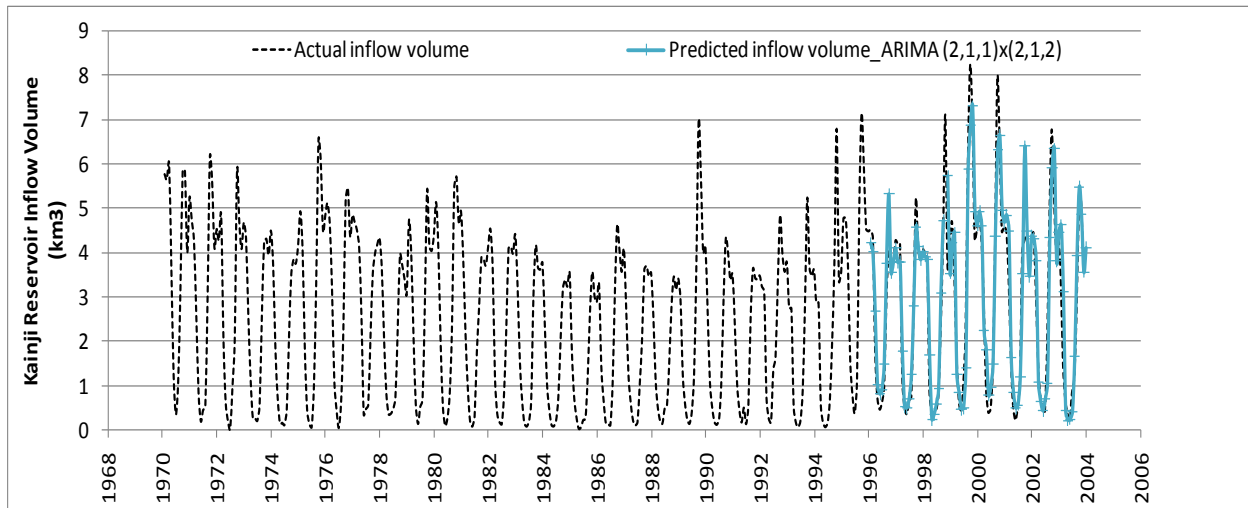


Figure 30: Time series of actual vs. predicted inflow volume from ARIMA (2,1,1)x(2,1,2)₁₂ model

Model Summary			
DF	377	Stable	Yes
Sum of Squared Errors	179.719817	Invertible	Yes
Variance Estimate	0.47671039		
Standard Deviation	0.69044217		
Akaike's 'A' Information Criterion	827.38485		
Schwarz's Bayesian Criterion	859.010797		
RSquare	0.86535094		
RSquare Adj	0.8628964		
MAPE	53.1443808		
MAE	0.47283142		
-2LogLikelihood	811.38485		

Figure 31: Summary of ARIMA (2,1,1)x(2,1,2)₁₂ model

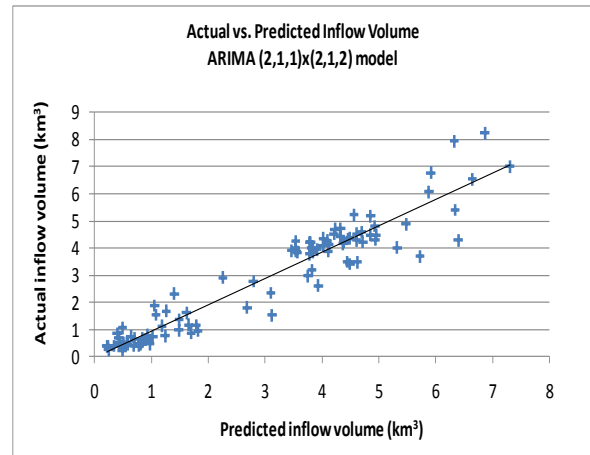


Figure 32: Actual vs. predicted inflow volume from ARIMA ARIMA (2,1,1)x(2,1,2)₁₂ model. ($R^2=0.87$)

Overall, the results from the models compared showed the suitability for forecasting inflows and inflow volumes to the reservoir. In some cases, there were differences between their order of integration, order or autoregression, and the moving average order. But in each case, the physical

behavior of the system was adequately represented by the models. The Bayesian information criterion and Akaike's information criterion measure relative goodness of fit of the models. The Dickey-Fuller (DF) test results which gives indications of the presence of unit roots in the time series suggests model stability in all three cases. The mean absolute percent error (MAE) is a measure of the average magnitude of the errors in a set of forecasts and their magnitude in all three cases were acceptably low. The MAE is also the mean over the verification sample of the absolute values of the differences between forecasts and the corresponding observations. The values of mean absolute percent error (MAPE) appear larger than the MAE due to a known insignificant error arising from the relatively small denominators in the percent error equation and their total summation.

In Figure 33, just like in the previous models tested, the ACF and PACF of the model both show evidence of randomness about zero. Similarly, the ACF also decays to zero before the first five lags. This rapid decay to zero before the 5th lag of the ACF indicates seasonality of the series.

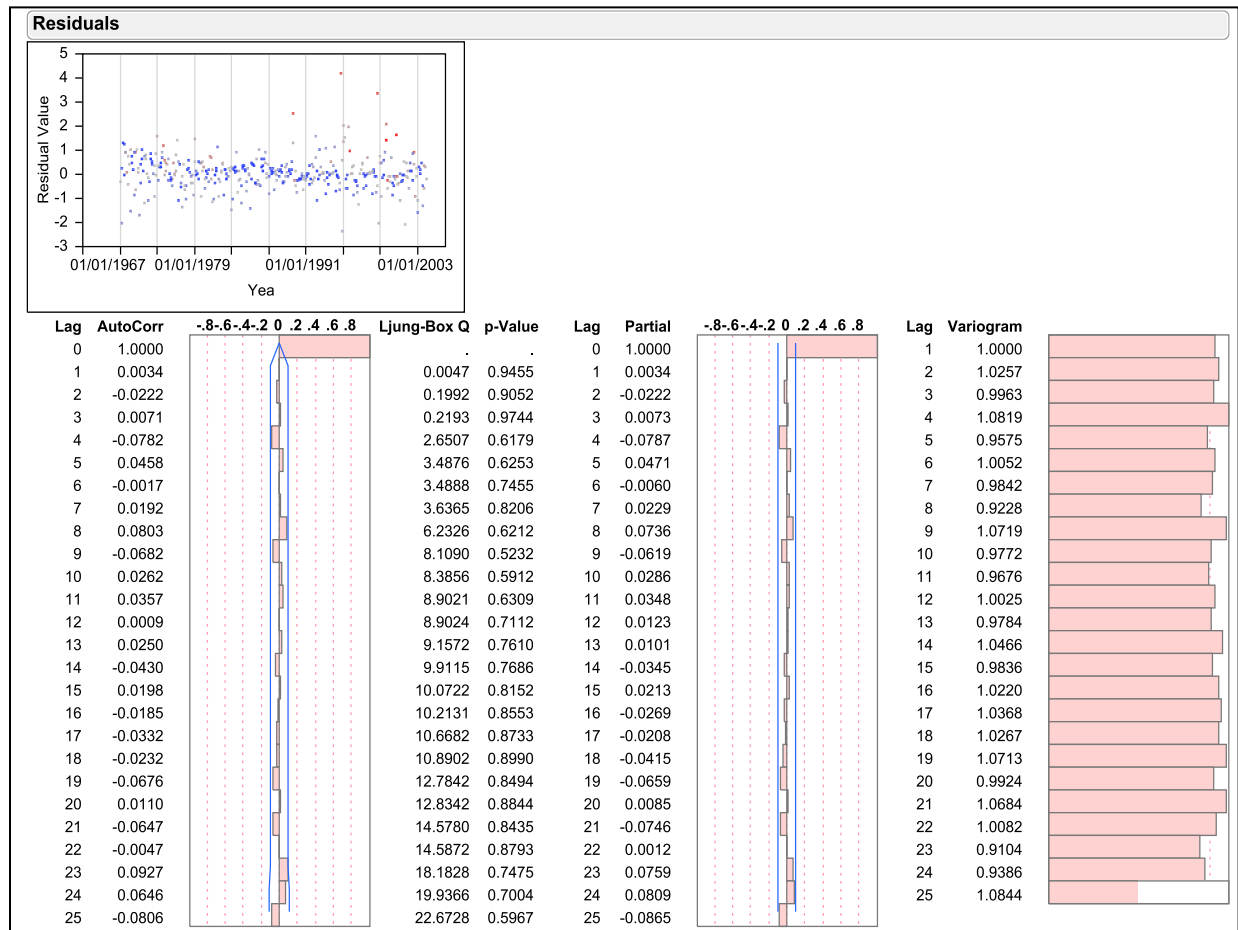


Figure 33: ACF and PACFs of ARIMA (2,1,1)x(2,1,2)₁₂ model

In Table 7, a selected sample of data and results from a two-year (2000-2001) period is presented. The forecast results are presented as well. A side-by-side comparison on the actual inflow volume and the predicted inflow volume is shown along with the respective upper and lower confidence limits of the results. The average relative error between forecasted inflow volume and actual inflow volume is about 9.6% suggesting that the ARIMA (2,1,1)x(2,1,2)₁₂ model is the most reliable of the best three models presented and the best of all those studied.

Table 7: Actual vs. predicted inflow volumes from ARIMA (2,1,1)x(2,1,2)₁₂ model

Month	Actual inflow volume at Kainji dam (km3)	Predicted inflow volume at Kainji dam (km3)	Std Err Pred Volume (km3)	Residual Volume (km3)	Upper CL (0_95) Volume (km3)	Lower CL (0_95) Volume (km3)	Relative error (%)
01/01/2000	4.8184416	4.933081365	0.69044217	-0.1146398	6.286323153	3.57984	2.3791876
02/01/2000	4.2892416	4.611143663	0.69044217	-0.3219021	5.964385451	3.257902	7.5048713
03/01/2000	2.9140992	2.756352466	0.69044217	0.15774673	3.609594254	0.903111	5.4132246
04/01/2000	0.953856	0.817206563	0.69044217	0.13664944	3.17044835	0.463965	14.326003
05/01/2000	0.3964032	0.383154685	0.69044217	0.01324852	2.136396472	-0.57009	3.3421818
06/01/2000	0.469152	0.572086673	0.69044217	-0.1029347	2.325328461	-0.38116	21.940581
07/01/2000	1.3606272	1.489970896	0.69044217	-0.1293437	2.843212684	0.136729	9.5061818
08/01/2000	4.1622336	4.371133393	0.69044217	-0.2088998	5.724375181	3.017892	5.0189349
09/01/2000	7.94448	6.3259653	0.69044217	1.6185147	7.679207087	4.972724	20.372821
10/01/2000	6.5326176	6.644525155	0.69044217	-0.1119076	7.997766943	5.291283	1.7130584
11/01/2000	4.48416	4.952611444	0.69044217	-0.4684514	6.305853232	3.59937	10.446805
12/01/2000	4.6041696	4.693988501	0.69044217	-0.0898189	6.047230289	3.340747	1.9508165
01/01/2001	4.4836416	4.851638527	0.69044217	-0.3679969	6.204880315	3.498397	8.2075456
02/01/2001	3.4086528	4.493356306	0.69044217	-1.0847035	5.846598094	3.140115	31.822059
03/01/2001	1.6123968	1.6177481	0.69044217	-0.0053513	2.970989888	0.264506	0.3318848
04/01/2001	0.520992	0.530898456	0.69044217	-0.0099065	2.184140244	-0.52234	1.9014604
05/01/2001	0.2196288	0.28873851	0.69044217	-0.0691097	1.841980298	-0.8645	31.466597
06/01/2001	0.508032	0.564059792	0.69044217	-0.0560278	1.91730158	-0.78918	11.028398
07/01/2001	1.1276064	1.186553397	0.69044217	-0.058947	2.539795185	-0.16669	5.2276217
08/01/2001	4.0229568	3.536918875	0.69044217	0.48603792	4.890160663	2.183677	12.081609
09/01/2001	4.284576	4.598133502	0.69044217	-0.3135575	7.75137529	5.044892	7.3182855
10/01/2001	4.3738272	4.487469572	0.69044217	-0.1136424	5.84071136	3.134228	2.5982364
11/01/2001	3.903552	3.468035471	0.69044217	0.43551653	4.821277259	2.114794	11.156929
12/01/2001	4.2345504	4.381749647	0.69044217	-0.1471992	5.734991435	3.028508	3.4761482
						Average =	9.6054767

In Table 8, a comparison of all forecasted inflows with actual inflows is shown. The advantage of the ARIMA (2,1,1)x(2,1,2)₁₂ model over the others is evident. This model was hence adopted for use in all inflow forecast purposes given its reliability.

Table 8: Actual vs. all predicted inflow volumes from ARIMA models

Month	Actual inflow volume at Kainji dam (km3)	Predicted inflow ARIMA (101)x(011) (km3)	Predicted inflow ARIMA (111)x(212) (km3)	Predicted inflow ARIMA (211)x(212) (km3)	Relative Error in ARIMA (101)x(011) Model (%)	Relative Error in ARIMA (111)x(212) Model (%)	Relative Error in ARIMA (211)x(212) Model (%)
01/01/2000	4.8184416	4.340854458	4.763316182	4.933081365	9.91	1.14	2.38
02/01/2000	4.2892416	4.052091276	4.427243163	4.611143663	5.53	3.22	7.50
03/01/2000	2.9140992	1.748623257	2.087439782	2.756352466	39.99	28.37	5.41
04/01/2000	0.953856	1.49014553	1.579576628	0.817206563	56.22	65.60	14.33
05/01/2000	0.3964032	0.501693282	0.425553982	0.383154685	26.56	7.35	3.34
06/01/2000	0.469152	0.616117133	0.520856573	0.572086673	31.33	11.02	21.94
07/01/2000	1.3606272	1.134159797	1.34567862	1.489970896	16.64	1.10	9.51
08/01/2000	4.1622336	3.793655334	4.24756879	4.371133393	8.86	2.05	5.02
09/01/2000	7.94448	5.95179996	6.234514768	6.3259653	25.08	21.52	20.37
10/01/2000	6.5326176	6.843613365	6.468917263	6.644525155	4.76	0.98	1.71
11/01/2000	4.48416	4.446613295	4.91804756	4.952611444	0.84	9.68	10.45
12/01/2000	4.6041696	4.495202633	4.695467865	4.693988501	2.37	1.98	1.95
01/01/2001	4.4836416	4.497875371	4.761919228	4.851638527	0.32	6.21	8.21
02/01/2001	3.4086528	3.887062418	4.400355156	4.493356306	14.04	29.09	31.82
03/01/2001	1.6123968	1.512191	1.543169809	1.6177481	6.21	4.29	0.33
04/01/2001	0.520992	0.534871811	0.624069518	0.530898456	2.66	19.78	1.90
05/01/2001	0.2196288	0.261412059	0.279572489	0.28873851	19.02	27.29	31.47
06/01/2001	0.508032	0.471014355	0.489608303	0.564059792	7.29	3.63	11.03
07/01/2001	1.1276064	1.224067664	1.11973503	1.186553397	8.55	0.70	5.23
08/01/2001	4.0229568	3.731822562	3.513905082	3.536918875	7.24	12.65	12.08
09/01/2001	4.284576	6.426179679	6.377920546	4.598133502	49.98	48.86	7.32
10/01/2001	4.3738272	4.35689354	4.659359052	4.487469572	0.39	6.53	2.60
11/01/2001	3.903552	3.278897555	3.261743214	3.468035471	16.00	16.44	11.16
12/01/2001	4.2345504	4.256436989	4.258733676	4.381749647	0.52	0.57	3.48
Average =					15.01	13.75	9.61

A summary of all model parameter estimates is shown in Figure 34. These refer to the numerical values of the respective lags applied, estimates of the model operators, standard error of each run, and the t ratio, which measures the ratio of the departure of an estimated parameter from its standard error and notional value.

ARIMA (1, 0, 1) x (0, 1, 1) ₁₂ model summary							
Parameter Estimates							
Term	Factor	Lag	Estimate	Std Error	t Ratio	Prob> t	Constant Estimate
AR1,1	1	1	0.5527379	0.0718885	7.69	<.0001*	
MA1,1	1	1	-0.1026055	0.0897427	-1.14	0.2536	-0.0096975
MA2,12	2	12	0.7197698	0.0436961	16.47	<.0001*	
Intercept	1	0	-0.0216820	0.0259542	-0.84	0.4040	

ARIMA (1, 1, 1) x (2, 1, 2) ₁₂ model summary							
Parameter Estimates							
Term	Factor	Lag	Estimate	Std Error	t Ratio	Prob> t	Constant Estimate
AR1,1	1	1	0.588997	0.0707027	8.33	<.0001*	
AR2,12	2	12	0.353861	0.1785645	1.98	0.0482*	0.00054399
AR2,24	2	24	-0.294529	0.1023182	-2.88	0.0042*	
MA1,1	1	1	0.954813	0.0434419	21.98	<.0001*	
MA2,12	2	12	1.042207	0.1809592	5.76	<.0001*	
MA2,24	2	24	-0.351080	0.1721410	-2.04	0.0421*	
Intercept	1	0	0.001407	0.0016474	0.85	0.3936	

ARIMA (2, 1, 1) x (2, 1, 2) ₁₂ model summary							
Parameter Estimates							
Term	Factor	Lag	Estimate	Std Error	t Ratio	Prob> t	Constant Estimate
AR1,1	1	1	0.590843	0.0676267	8.74	<.0001*	
AR1,2	1	2	-0.133869	0.0571488	-2.34	0.0197*	0.00073555
AR2,12	2	12	0.312321	0.1792923	1.74	0.0823	
AR2,24	2	24	-0.275565	0.1007539	-2.74	0.0065*	
MA1,1	1	1	0.896091	0.0475613	18.84	<.0001*	
MA2,12	2	12	1.013657	0.1843626	5.50	<.0001*	
MA2,24	2	24	-0.312366	0.1734380	-1.80	0.0725	
Intercept	1	0	0.001406	0.0024514	0.57	0.5665	

Figure 34: Summary of all ARIMA models.

3.7.4 Jebba Reservoir Inflow Modeling

The same seasonal multiplicative ARIMA models were applied to modeling Jebba reservoir inflows. These were done using inflows from 1984 when the Jebba dam completion and data collection began to 2000 to allow for a large enough observed dataset. Then inflow data from 2001 to 2003 were used for model validation, as shown in the time series comparison in Figure 35. The closest result was a ARIMA (1,1,1)X(2,1,2)₁₂ with a determination coefficient of 0.59.

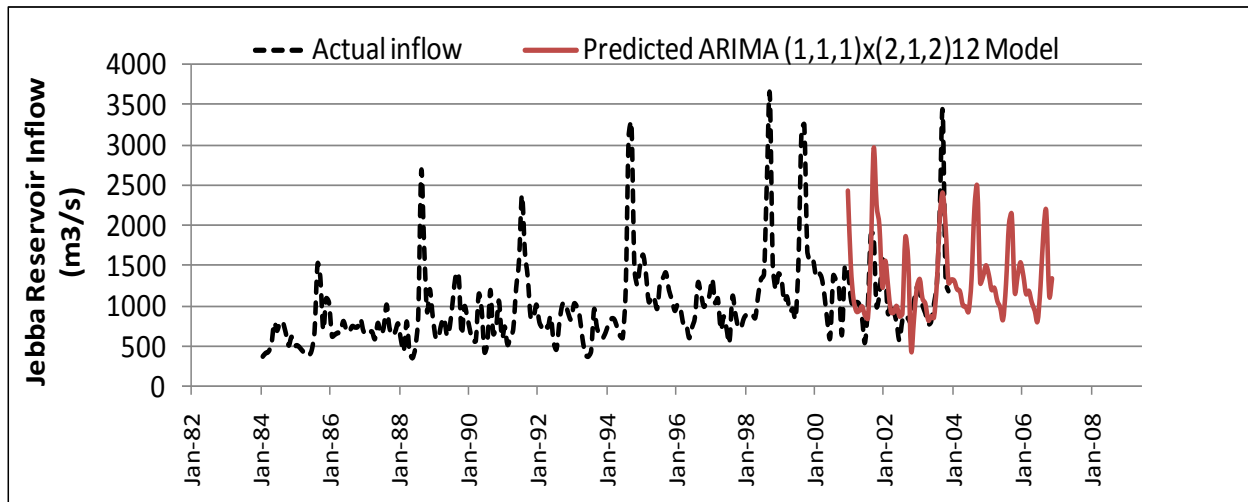


Figure 35: Time series comparison of Actual and Forecasted Inflows at the Jebba Reservoir

A lack of true seasonality in the inflows usually responsible for such results was confirmed in the ACF and PACFs as shown in Figure 36. There is no strong evidence of randomness about zero. Also, the ACF does not reflect the decay to zero before the first five lags observed in the previous models.

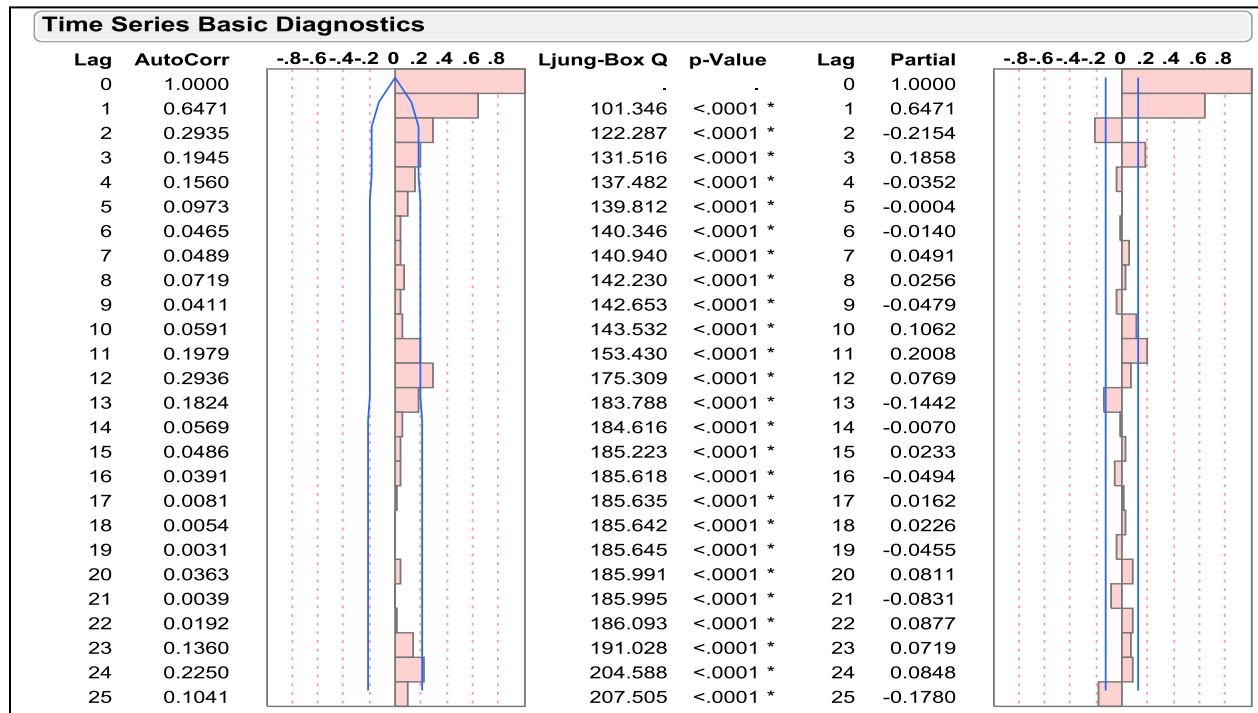


Figure 36: ACF and PACF of Forecasted Inflows at the Jebba Reservoir

3.8 Conclusions

In every case applied for forecasting Kainji reservoir inflows, the models with the highest reliability were multiplicative ARIMA (p,d,q) x (P,D,Q)₁₂ models of the variety discussed and whose results are presented above. This is evidenced in the similarity in measured and forecasted datasets. But none of these models worked for inflows to Jebba reservoir. According to Box and Jenkins (1970), no guidelines exist for the initial estimate values; rather various values have to be experimented. For Jebba reservoir inflows, the resulting forecasts and their errors that did not show any evidence of randomness about zero. Therefore, the model was considered unreliable and discarded. The lack of true seasonality in Jebba inflows may be responsible. Inflows to the

Jebba reservoir depend strongly on release patterns at the upstream Kainji reservoir. These release patterns are mostly determined by human operators hence the lack of seasonality suggests that the physical behavior of the system lacks an important, natural seasonal characteristic for which reliable stochastic modeling is often possible. Modeling of inflows to the Jebba reservoir is perhaps not as important as at the much larger and hydrologically significant Kainji reservoir. Since the outflow from Kainji forms the inflow to Jebba and since Jebba reservoir capacity is about 20% that of Kainji, a thorough understanding of inflow forecasts for the Kainji reservoir system should yield a good deal of information to adequately manage the Jebba reservoir.

CHAPTER 4:

VALIDATION OF RESERVOIR ALTIMETRIC LEVELS AND INFLOW RATING CURVES

This chapter has been published in the *International Journal of Water Resources and Environmental Engineering* with the following citation:

Salami, Y., and Nnadi F., (2012a)., "Seasonal and Interannual Validation of Satellite-Measured Reservoir Levels at the Kainji Dam", *Int. J. Water. Res. Environ. Eng.* Vol 4(4), pp. 105-113.

4.1 Introduction

The availability of water and the effective management of a nation's water resources are closely linked because availability of water precedes and necessitates its management. Therefore, there is a constant need by water administrators, both regionally and globally, to balance water quantity with proper management techniques. However, seasonal dependence of both availability and demand has created the necessity for sustenance initiatives between one season and the next. To this, reservoirs have provided a convenient solution given their ability to hold water from natural systems until it is needed for use. Sometimes the balance between availability of water and effective water management becomes strained as is the case with the Kainji reservoir in Nigeria, where drastically low water levels in the dry months and flooding in the rainy season have frequently occurred within the same year (Emoabino et al., 2007).

Where reservoirs form the focus of a nation's reliance for flood control, navigation, hydropower, and irrigation like the Kainji reservoir does for Nigeria, it becomes imperative to develop a readily available and reliable method of predicting and quantifying the availability of water in

the reservoir for these purposes. For example, directly measuring storage or inundation area may be difficult but storage-stage and area-stage curves, where available for a given reservoir, are extremely useful estimation tools (Magome et al., 2003). But first, stage must be readily obtainable and reliable. Conventional technologies for monitoring stage and discharge typically provide water managers with ample foundational water quantity information. But in most of Africa where some technologies and policies already exist but are hampered by maintenance and implementation respectively, a supplementary solution is desired. In order for such a solution to be admissible as a water resources management tool, it must be cost-effective, able to supplement or replace conventional technologies, require little human supervision, must not be subject to administrative barriers or political interference, and must be demonstrably reliable over long periods. Satellite radar altimeters, devices used for remotely measuring water surface heights from space, hold the key. Their applications have been demonstrated in coastal waters and oceans, but they have also seen some successful use in inland waters (Cretaux & Birkett, 2006).

This study investigated:

- (1) the interannual applicability of Kainji Lake altimetry data to lake level monitoring
- (2) the seasonal applicability of altimetry data (for different seasons of the year) to understanding seasonal lake level variations.
- (3) which satellite altimeter data gives the highest determination coefficients and lowest RMS errors and therefore can complement gage data for Kainji reservoir level monitoring.

4.2 Background of Satellite Altimeters and Kainji Reservoir

It is not possible to completely observe all inland waters that utilize gages. But satellites have made it easier to monitor, quantify and manage water resources without direct human presence. Principally, this occurs by remote measurement of water surface elevation. The technology, known as satellite radar altimetry, has been demonstrated to yield highly accurate results both regionally and globally (Birkett, 1998). Unlike imaging instruments, altimeters only collect elevations along a narrow path determined by the principle of pulse-limited dual-frequency radar altimeter. The actual footprint diameter depends on the nature of the target, and can range from several hundred meters to many kilometers. While originally conceived of for use in larger water bodies like oceans and seas, satellite radar altimeters have been frequently and extensively used in inland waters (Cretaux and Birkett, 2006). Where inland surface waters are concerned, it has been shown that remote measurements of water level measured by satellite altimeters yields appreciably high correlations with water elevation measured by in situ gages. Cretaux and Birkett (2006), and Zhang et al. (2006) demonstrated this for Lake Chad, Africa and Lake Dongting, China respectively. But more specifically, this study seeks to take the validation task a step further by conducting temporally sensitive seasonal comparisons between gage and satellite data. While year-long comparisons seem sufficient, they may not reveal the possibility that hydrological and operational factors in dammed lakes may affect the outcome and reliability of validation. While some studies have shown adequately high correlation of gage and satellite data for specific reservoirs as with Lake Dongting, China, (Zhang et al., 2006) a few others have revealed comparatively lower correlations as shown in the studies performed on Lake Kivu,

Rwanda (Munyaneza et al., 2009). Various reasons exist for such dissimilarities, such as poor quality of gage data. Mismatches of data due to poor quality of altimeter data can arise from extreme precipitation events, backwater effects, temporal and spatial resolution limitations, irregular geomorphology of channel, erratic orbit of altimeter, etc. ('Surface monitoring by satellite altimetry').

Also, Kainji reservoir operators typically adopt the operational policies of the previous year for operation and management the following year (Onemayin, 2008). This practice is ascribed to the 1999 flooding of the Kainji plains where operational policies for dam operation adopted by the managers in the late 1990s were unable to adequately cater for the sudden high inflows experienced. The sudden decision to deliberately release water to ease dangerously rising stage and protect the dam's structural integrity flooded more than 40 villages, and caused damage to farmland and other property worth millions of dollars. It is therefore hoped that altimetry can be used to complement reservoir level data in such seasons. In addition, farmers on the banks of the Kainji reservoir directly depend on reservoir elevation for irrigation. Therefore, water demand for irrigation uses can be adequately catered for and estimated directly from altimetric levels and stage-storage curves. Where backwater effects and flood waves may skew gage measurements, the moving averages derived by satellite altimeters can provide an alternative basis of stage comparison for use in storage estimation. Also, reservoirs located in semi-arid regions typically experience little direct precipitation but depend on runoff for increased storage (Liebe et al., 2005). In such cases, when water demand exceeds recharge rates and the reservoir drawdown hits minimum levels, sporadic patches or pools of water begin to appear and satellite-measured stage ceases to accurately reflect the average depth of the reservoir. Correlation between

altimeter and gage levels is often directly related to the physical proximity of the altimeter path to gage locations. It has also been suggested that the resolution of satellite altimeters can determine the extent of their correlation to gage data, especially if the gage data is only marginally distinct from altimetry (Birkett, 1998). It was also observed that satellite passes that cross narrow reservoir extents, like the dam site of the Kainji reservoir, and difficult terrain will stretch the limits of the instruments. The resulting root-mean-square errors can amount to many tens of centimeters (Cretaux et al., 2001). In Figure 37, the spatial coverage of altimeters over Kainji reservoir can be observed.

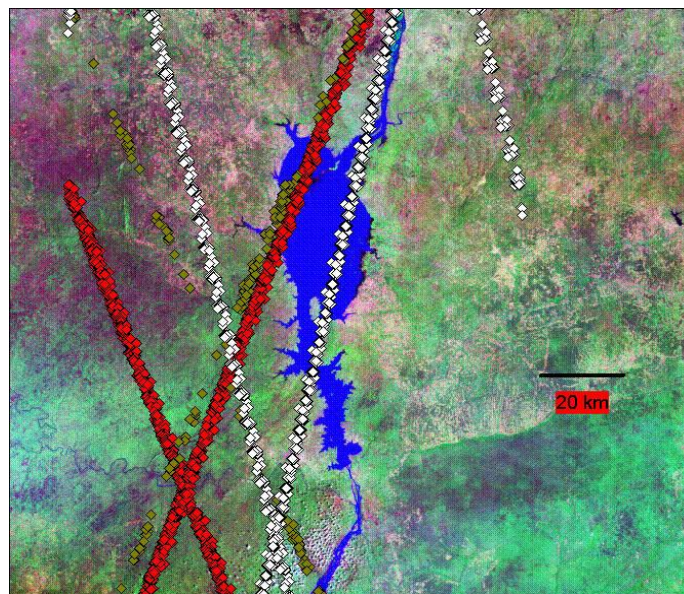


Figure 37: Altimeter Pass points over Kainji reservoir. (White Lines: ERS and ENVISAT, Red Lines: T/P and JASON-1, Olive lines: GFO. These indicate nominal ground tracks. A drift up to +/- 1km is expected in actual operation) Source: 'Surface monitoring by satellite altimetry'.

4.2.1 Previous Case Study: Lake Kivu Satellite-measured water level validation

A study on Lake Kivu (which straddles the countries of Rwanda and the Republic of Congo) investigated the use of satellite radar altimetry for lake level monitoring (Munyaneza et al., 2009). Figure 38 shows the times series comparison.

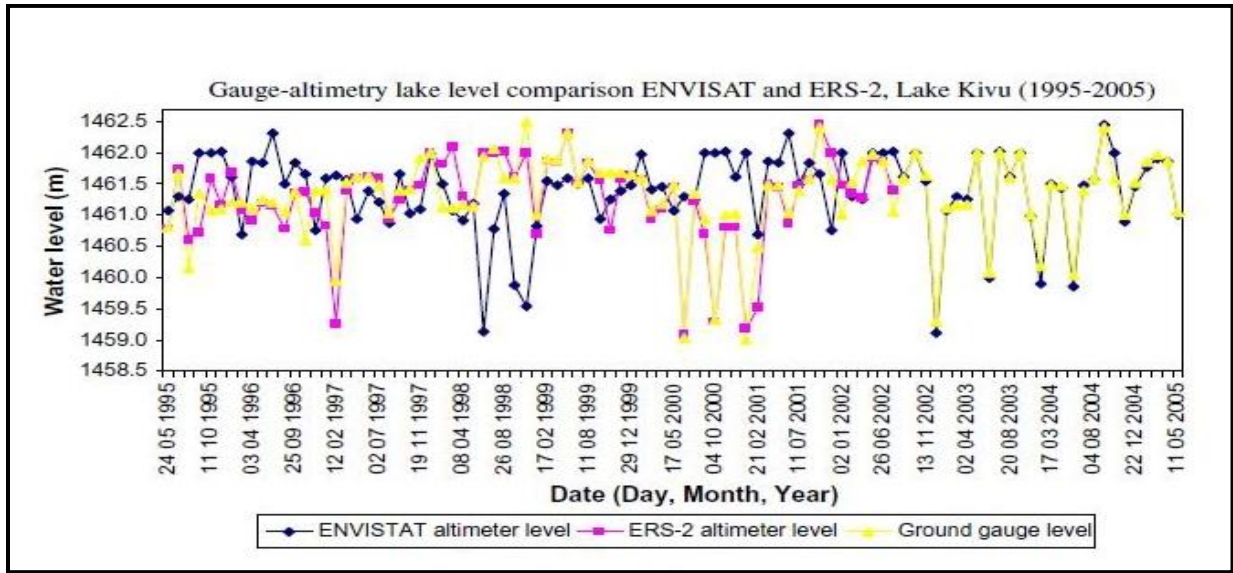


Figure 38: Altimetric Level Validation for Lake Kivu, Rwanda (Munyaneza, et al., 2009)

Lake Kivu has an estimated water volume of $500 \times 10^9 \text{ m}^3$, a surface area of 2400 km^2 with 1000 km^2 of this located in Rwanda. It is located 1460 m above sea level. Conventional field gages were used to monitor lake surface elevation for a ten year period (1995-2005) and the data compared with ENVISAT and ERS altimeter data sets for the same period. The results showed a higher correlation coefficient for ENVISAT altimeter ($R^2=0.85$) than for ERS altimeter ($R^2 = 0.77$) (Figure 39 and Table 9).

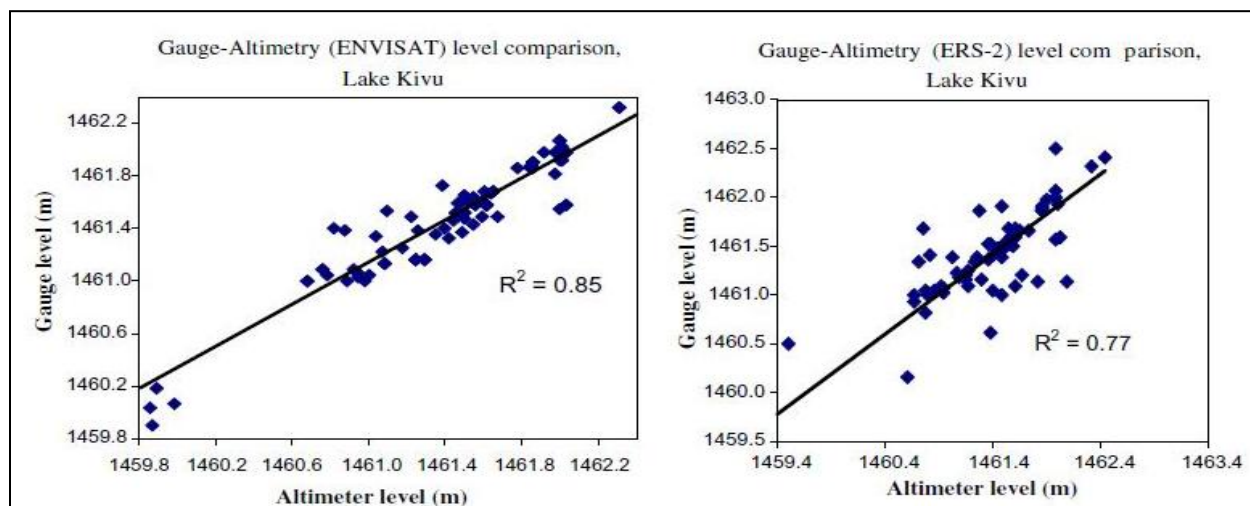


Figure 39: Altimeter-Gage Comparison for Lake Kivu, Africa (Munyaneza et al., 2009).

Table 9: Summary of Results of Altimeter-Gage Comparison for Lake Kivu, Africa. (Munyaneza et al., 2009)

Parameter	ENVISAT	ERS-2	Combined ENVISAT and ERS-2
RMSE (m)	0.254	0.339	0.294
R^2	0.855	0.769	0.955
Std. deviation of error (m)	0.642	0.701	0.669
Mean lake level (m)	1461.39	1461.26	1461.31

In summary, the Lake Kivu study yielded reasonable values of standard deviation and root-mean-square errors values between satellite-measured and field-measured lake levels. Although this lake is a more inland water body shared by two countries, it appears the technology can be used in the absence of functional gages for remote water level or flow estimation especially with combined altimeter data sets.

4.3 Experimental Details and Methodology

4.3.1 Study Area

The Kainji Lake (See Figure 40) was created by impounding the Niger River in the late 1960s during the construction of Kainji hydroelectric dam. It is located between latitudes 9°50' N and 10°35'N and longitudes 4°26'E and 4°40'E. The reservoir measures about 135 km in length and is about 30 km at its widest point. It covers an estimated surface area of 1270 km² and has a capacity of 15 x 10⁹ m³. The characteristics of the reservoir are presented in Table 10. The river runs through more than five countries and is Africa's longest at more than 4000 km. The Kainji reservoir depends mainly on inflow from the Niger River for sustenance of the country's electricity demands. Runoff from its surrounding catchment accounts for less than 10% of inflow (Onemayin, 2008).

Table 10: Characteristics of Kainji Reservoir

Characteristics of Kainji Reservoir	
Latitude	9°50' N
Longitude	4°40' E
Maximum Capacity (m ³)	15 x 10 ⁹
Minimum Capacity (m ³)	3.5 x 10 ⁹
Surface Area (km ²)	1270
Length (km)	135
Maximum Width (km)	30
Maximum Elevation (m.a.s.l.)	141.9

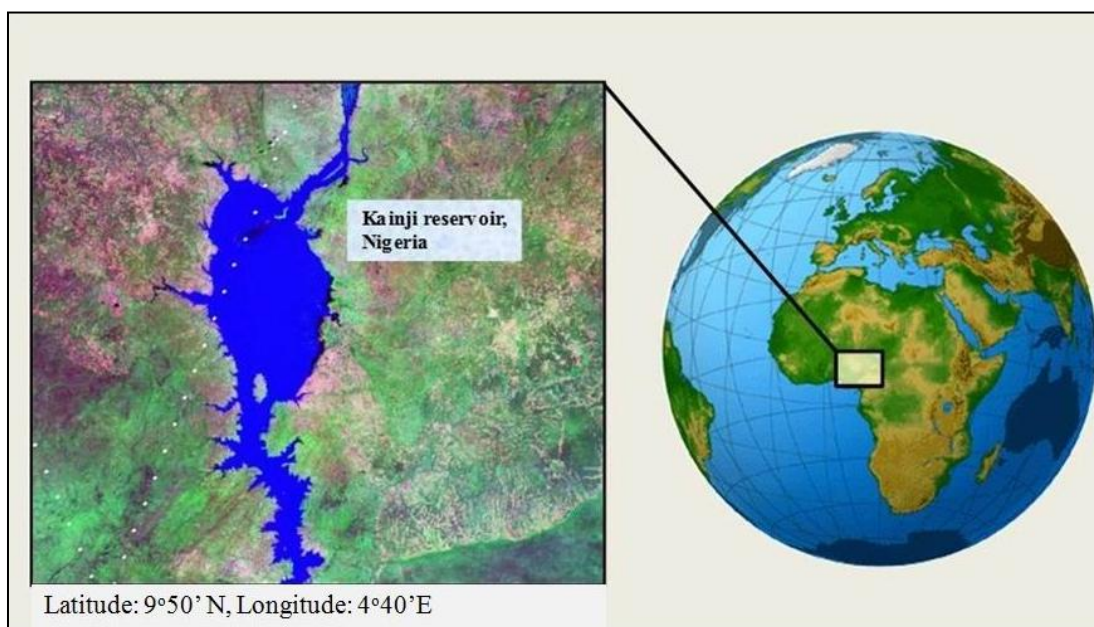


Figure 40: Location of Kainji Lake (White dots: T/P satellite altimeter tracks)

4.3.2 Data Collection

Gage Data

Daily and monthly averages of water level within the Kainji reservoir were obtained for the 1992-2002 period. The monthly averages were obtained for use in the time series plots, while daily data were used to determine correlations. All gage stage data was measured relative to a datum. Though not the same datum as that in the satellite altimeter data, the relative heights are comparable as both measurements (altimeter and gage) represent relative changes in elevation. Different vertical axes were adopted for each separate series for coincident time frames.

Satellite Altimeter Data

This study used two separate data sets of altimetry data for the 1992-2002 period:

- (i) Topex/Poseidon (T/P)
- (ii) ERS/ENVISAT

Both sets of altimeter data are freely available online for continental ocean surfaces, and many rivers and reservoirs across the earth surface. T/P altimeter has a 10-day temporal resolution and a spatial resolution of 580 m, with global coverage stretching to North/South latitude 66 degrees. JASON-1 satellite mission replaced the T/P mission in 2003 after the latter had its orbit altered. ERS/ENVISAT altimeters measure water surface elevation at a temporal resolution of 35 days and at intervals of 380 m. The ENVISAT mission replaced the ERS-1 and ERS-2 European space missions in 2002 but they are still so referred. Additional information on the principle of altimeters and an extensive discussion of each satellite mission is presented by Birkett (1995 and

2000). The global coverage of both altimeters are shown in Figure 41 and Figure 42. ENVISAT and T/P datasets used are relative to WGS84 and GGM02C height systems respectively.

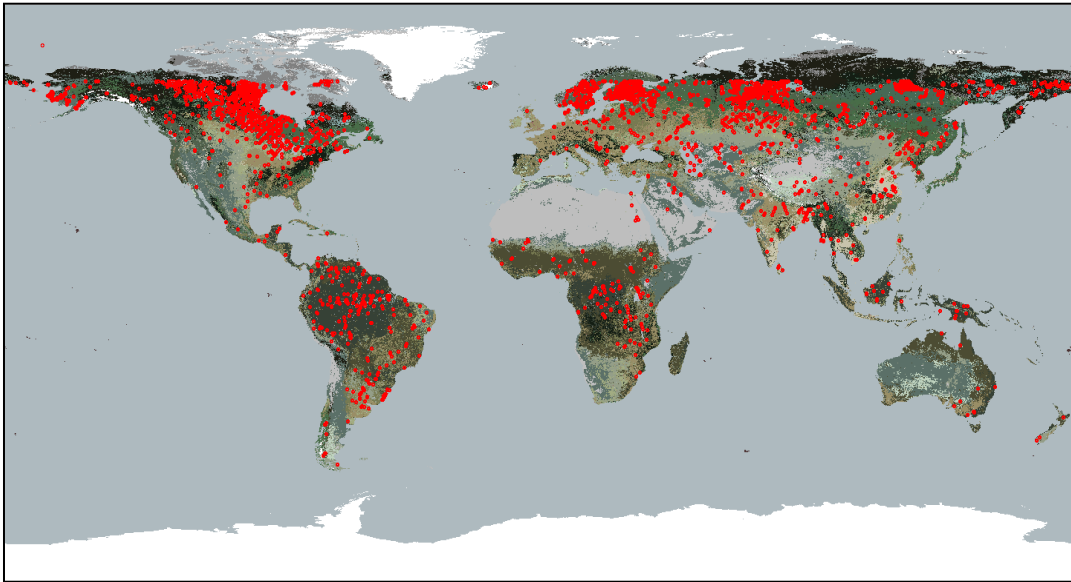


Figure 41: TOPEX/Poseidon Global Targets (Source: European Space Agency; www.esa.int)

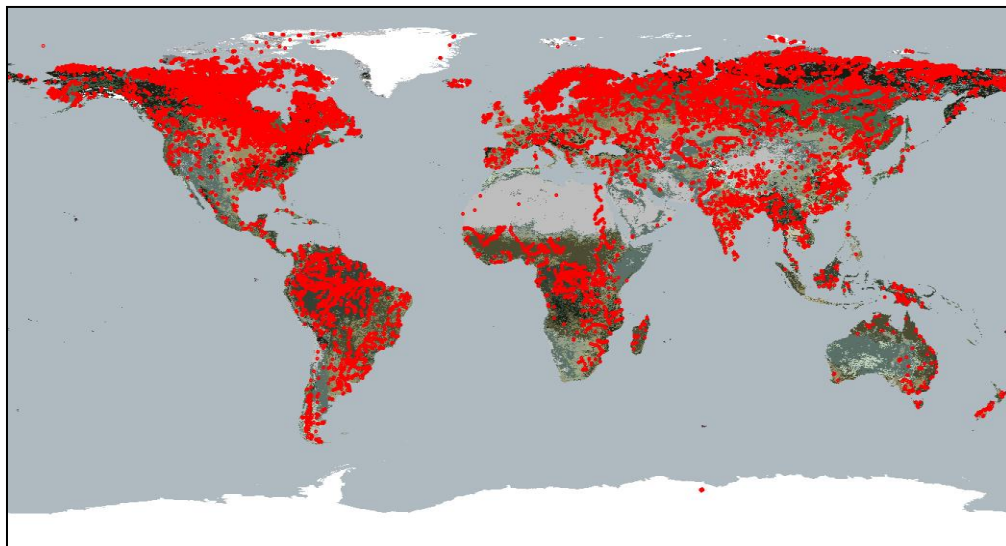


Figure 42: ENVISAT global targets (Source: www.esa.int)

4.3.3 Temporal Correction and Alignment

A summary of all data used such as source(s), collection dates, and ‘time series intervals’ is shown on Table 11. Here, X denotes the year in which data was measured. For this study, two main types of comparisons were made between gage levels and altimeter levels. First, a time series plot of gage level and altimeter levels was performed. A second set of comparisons were made to validate altimeter data, first interannually, then seasonally. The RMS errors and standard deviation of the differentiated time series were then determined and reported as an indication of the overall altimetric error.

Time Series Plots

To allow for a fair and concurrent comparison, the measurement dates of the gage data and both altimetry data sets were expressed in the form of ‘year plus fraction of year’ in which each was measured. For example, water surface elevation data measured by a gage on January 31, 1994 was converted to $1994 + \left(\frac{31}{365}\right)$ or 1994.0849. This way, both sets of altimeter data as well as gage data were expressed in a homogenous time format where dates within any year are expressed in decimals. Appropriate corrections were made for leap years by using 366 days for one year and 29 days for February for the time series plots. For the gage vs. ERS/ENVISAT altimeter time series, there was a slight but consistent vertical offset arising from differences in the respective reference points of the gage and altimeter instruments. However, the amplitude variations or water height variations were observed to be identical. Since only actual water height variations are more important in this study, the gage and altimeter datasets were plotted as

relative water levels or lake height variations as shown to reveal any differences or similarities in amplitude variation. In addition to homogenizing all three measurement scales (gage, and T/P and ERS/ENVISAT altimeters), the plot using same reference demonstrates the similarities in relative water heights and their preference over water surface elevations for such studies involving water level or volume monitoring. Alternatively, simply sliding gage and altimetry levels along the same vertical scale should also reveal any similarities in relative heights, in spite of different reference frames (C. Birkett, email communication). And as with the gage vs. altimeter plots, the amplitude variations are identical.

4.3.4 Data Validation Technique

Interannual validation refers to year-long comparisons of both datasets. This was done with both altimetric and stage data for 1992-2002. For seasonal validation the data were separated into: (i) high stage (or ‘dry’ season) (ii) low stage (or ‘wet’ season). The terms dry and wet are used loosely and are described below.

High Stage Period (‘Dry’ Season)

This occurs from October to March/April. Average precipitation and reservoir inflow are relatively low during these months. Given the increased demand for water in the dry season, managers ensure that operational and hydrological parameters of the reservoir are balanced in order to achieve high water levels in these months.

Low Stage Period ('Dry' Season)

This occurs from April/May to September. Precipitation and inflow to the reservoir are relatively high in these months. The need to accommodate both these hydrological input parameters leads managers to operate the reservoir with medium to low stage most of the wet season.

4.3.5 Spatial Correction

In Figure 43 which shows the satellite pass points of T/P altimeter and ERS/ ENVISAT altimeter, the altimetry data were taken from the satellite pass points at the same location as the gage. The lake levels and the altimetric water levels were compared and plotted.

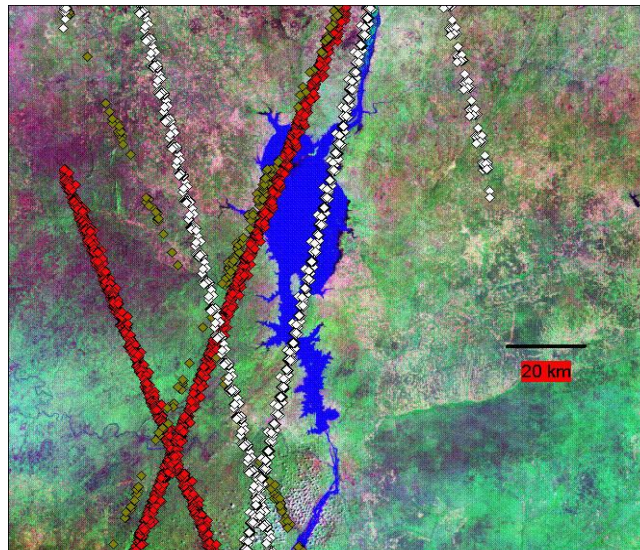


Figure 43: Altimeter Pass points over Kainji reservoir. (White Lines: ERS and ENVISAT, Red Lines: T/P and JASON-1, Olive lines: GFO. These indicate nominal ground tracks. A drift up to +/- 1km is expected in actual operation) Source: 'Surface monitoring by satellite altimetry'

Table 11: Summary of datasets used

Parameter	Measurement Device	Data Period Available	Temporal Resolution	Data points/Yr.	Time Series Progression (assuming year-end start date)
Lake Surface Height (m)	Gage	1970-2003	Daily; Monthly; Monthly Avg.	12	$X + \left(\frac{0}{365}\right), X + \left(\frac{31}{365}\right), X + \left(\frac{31+28}{365}\right), X + \left(\frac{31+28+31}{365}\right), \dots, X + \left(\frac{365}{365}\right)$
Lake Surface Height (m)	Satellite Radar Altimeter (Topex/Poseidon, JASON-1)	1992-2005, >2002	10 days	~9 - 12	$X + \left(\frac{0}{365}\right), X + \left(\frac{10}{365}\right), X + \left(\frac{20}{365}\right), X + \left(\frac{30}{365}\right), \dots, X + \left(\frac{365}{365}\right)$
Lake Surface Height (m)	Satellite Radar Altimeter (ERS-1, ERS-2, ENVISAT)	>1992	35 days	29 - 36	$X + \left(\frac{0}{365}\right), X + \left(\frac{35}{365}\right), X + \left(\frac{70}{365}\right), X + \left(\frac{105}{365}\right), \dots, X + \left(\frac{365}{365}\right)$

4.3.6 Alternative Validation of Forecasts of Reservoir Inflow

Since no current in situ inflow data was available to verify the predicted stream inflows and inflow volumes for the 2004-2015 period, a method was conceived to perform this check. The inflow gage location (Figure 44) at the Kainji reservoir lies along the track of Envisat and Topex/POSEIDON altimeter instruments for remote lake level measurements. Water surface elevations at this location are available from 1992 to date on NASA and ESA websites. Water levels measured at 35 day intervals by Envisat were then downloaded for 1992-2002 and matched with in situ measured reservoir inflows to generate the discharge rating curve shown.

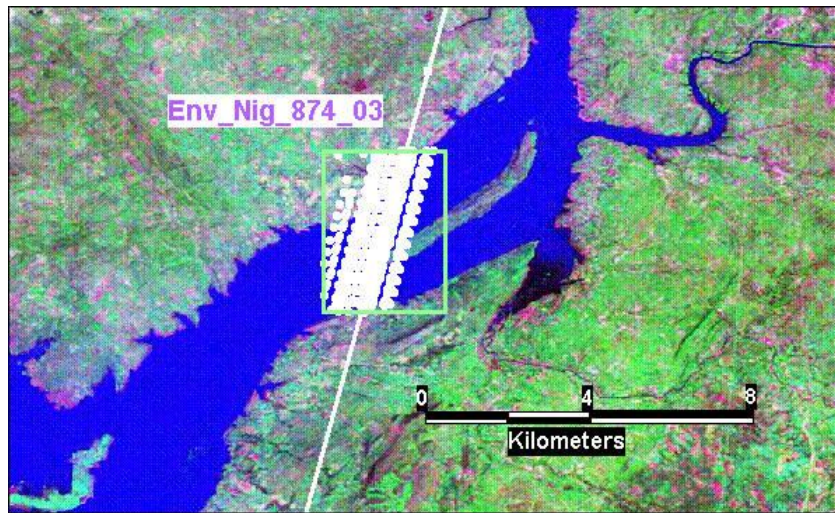


Figure 44: Envisat satellite altimeter tracks over Kainji reservoir inlet

Next, satellite-measured water levels for 2003-2011 were downloaded and inputted into the curve's equation to generate stream inflow values for 2003-2011 which were then compared with inflows generated from modeling. To ascertain the accuracy of satellite measured water levels, the following validation tasks were carried out to allowing for comparisons ground-measured and satellite-measured water levels in the Kainji reservoir area prior to testing the model. This was necessary because of the many factors on which the accuracy of satellite altimeters can depend on.

4.4 Results and Discussion

4.4.1 Time Series Plots of Lake Levels

For the gage vs. ERS/ENVISAT altimeter time series (Figure 45), there is a slight but consistent vertical offset arising from differences in the respective references of the gage and altimeter instruments. However, the amplitude variations or water height variations were identical. Since only actual water height variations are more important in this study, the gage and altimeter datasets were plotted as relative water levels or lake height variations as shown in Figure 46 to reveal any height differences or similarities in amplitude variation. In addition to homogenizing all three measurement scales (gage, T/P and ERS/ENVISAT altimeters), Figure 46 demonstrates the similarities in relative water heights and their preference over water surface elevations for such studies involving water level or volume monitoring. Alternatively, simply sliding gage and altimetry levels along the same vertical scale should also reveal any similarities in relative heights, in spite of different reference frames. As with the gage vs. altimeter plots in Figure 46, the amplitude variations are identical.

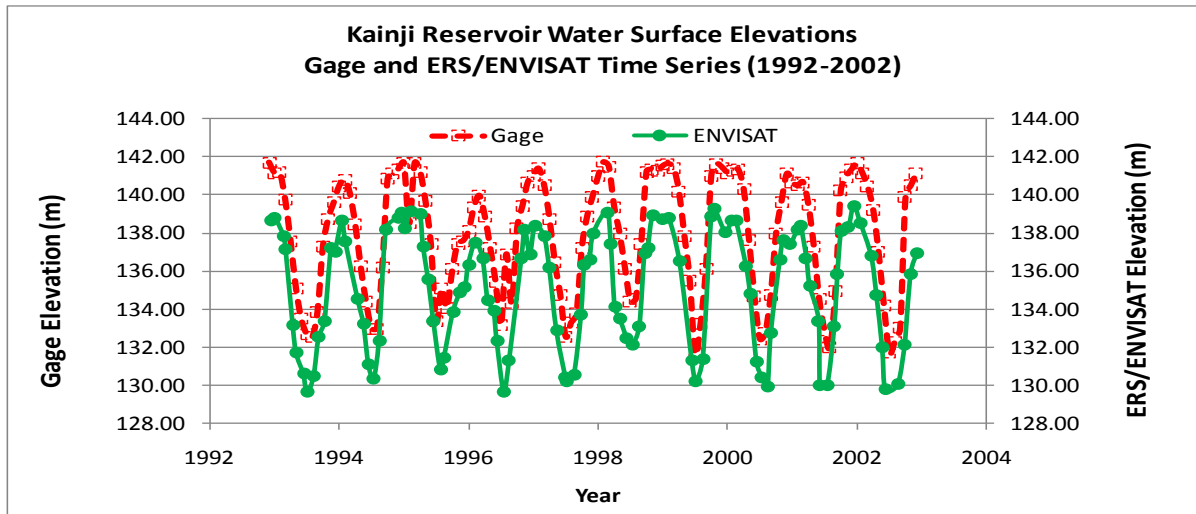


Figure 45: Time series plot of gage and ERS/ENVISAT altimeter lake surface elevation.

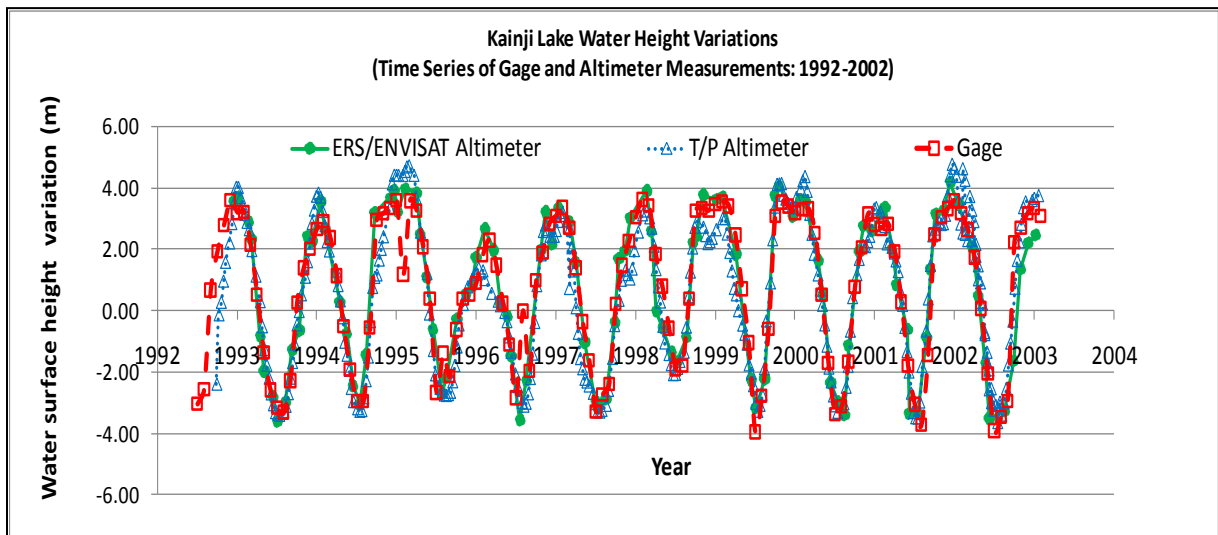


Figure 46: Time series plot of gage and altimeter lake water heights.

4.4.2 Interannual Validation Results.

The interannual comparison between T/P altimeter levels and gage levels suggested a coefficient of determination of 0.95, a RMS error of 0.54 m, and a standard deviation of 0.35 m. ERS/ENVISAT vs. gage comparison gave a coefficient of determination, RMS error, and standard deviation of 0.93, 0.55 m, and 0.29 m respectively (Figure 47, Figure 48 and Table 12).

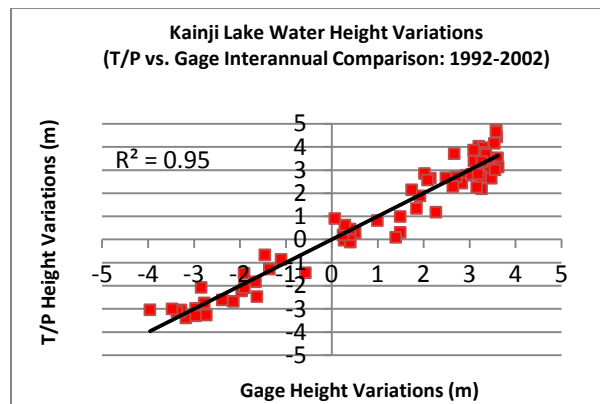


Figure 47: Interannual comparison of Kainji Lake height variations: T/P altimeter vs. gage

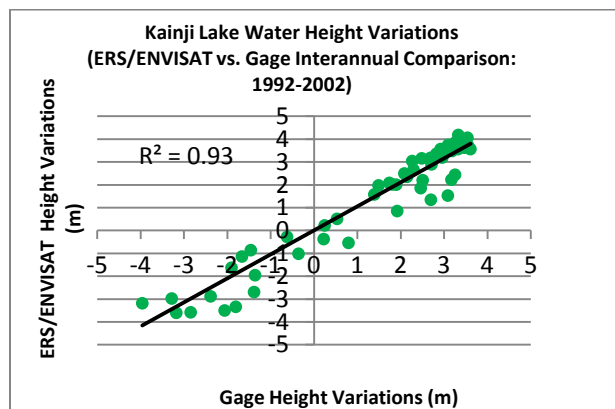


Figure 48: Interannual comparison of Kainji Lake height variations: ERS/ENVISAT altimeter vs. gage

4.4.3 Seasonal Validation Results

When T/P altimeter and gage height variations were compared for the dry seasons, this produced a determination coefficient, RMS error and standard deviation of 0.77, 0.77m and 0.70m respectively (Figure 49). Similarly, the comparison of ERS/ENVISAT and gage variations yielded 0.76, 0.83m and 0.80m respectively for the same tests (Figure 51). In comparing the wet season results for T/P altimeter, the determination coefficient, RMS error and standard deviation were 0.90, 0.50 m, and 0.24 m respectively (Figure 50), while ERS/ENVISAT vs. gage comparison gave 0.80, 0.59 m, and 0.47 m respectively (Figure 52). These are all summarized in Table 12.

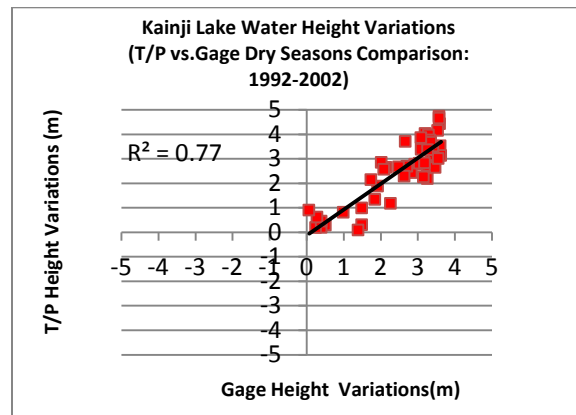


Figure 49: Kainji Lake height variations in dry season: T/P vs. gage

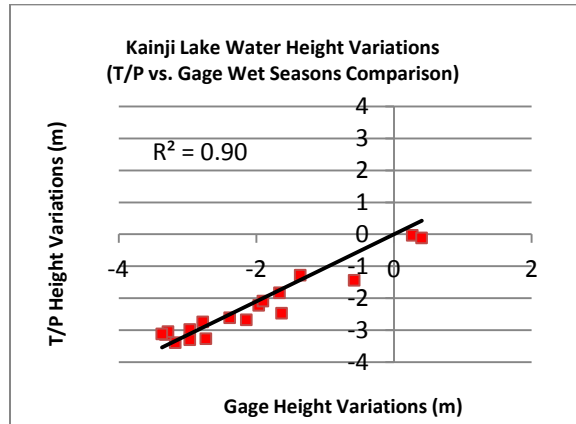


Figure 50: Kainji Lake height variations in wet season: T/P vs. gage.

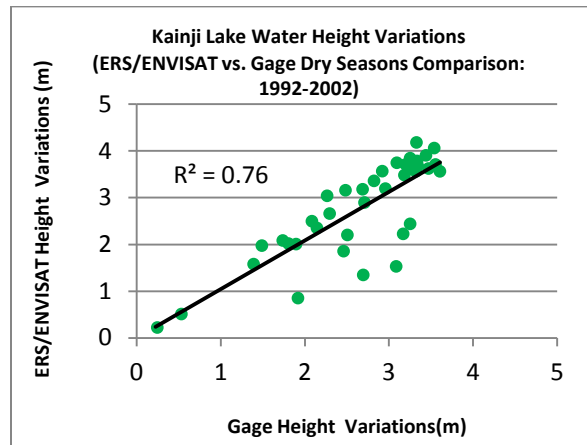


Figure 51: Kainji Lake height variations in dry season: ERS/ENVISAT vs. gage

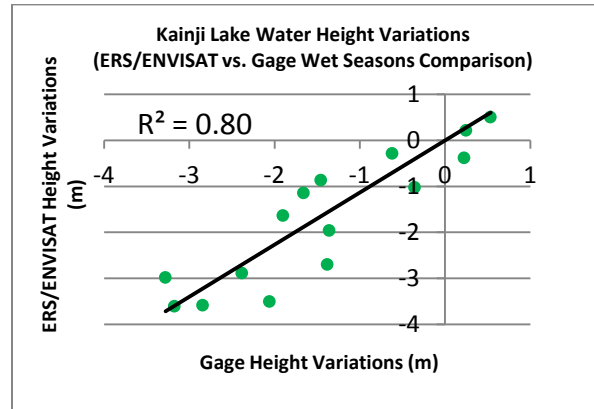


Figure 52: Kainji Lake height variations in wet season: ERS/ENVISAT vs. gage.

All RMS errors varied between 0.50 m and 0.83 m (see Table 12) demonstrating some consistency with previous studies. For instance, Birkett (1998) found that RMS errors varied depending on the size of the lake and the complexity of the contiguous topography. The RMS errors values range from 5 cm for large open lakes to many tens of centimeters for lakes that are smaller and shielded to those in deep valleys where the instrument only observes a narrow expanse of water (Cretaux et al., 2011) in which category the Kainji reservoir falls.

Also, the location of Kainji reservoir just south of the Sahel (a semi-arid region) suggests it experiences very dry, dusty harmattan winds typical of dry season as well as other windstorm events, possibly reducing the reliability of dry season altimeter-stage validation. In dry seasons (high stage), typical reservoir backwater effects create sharp storage variations. (Peng and Guo, 2006). The resultant temporal and spatial variations in stage within the reservoir at this period of the year may be responsible for lower seasonal correlation of altimetric measurements. The trend was the same for both satellite altimeters. The improved validation results observed in wet

season may be attributed to the relatively lower operational stage of the reservoir which is accompanied by calmer flow regimes within the reservoir. At such low stages and with only moderate precipitation events, backwater effects from the dam site are comparatively lower (Peng and Guo, 2006) at these times of the year, further improving the validation results.

Table 12: Summary of Validation Results

	Interannual		Seasonal			
	Gage vs. T/P	Gage vs. ERS/ENVISAT	Wet Season		Dry Season	
R² (%)	95	93	Gage vs. T/P	Gage vs. ERS/ENVISAT	Gage vs. T/P	Gage vs. ERS/ENVISAT
			90	80	77	76
RMS Error (m)	0.54	0.55	0.50	0.59	0.77	0.83
Std. Deviation (m)	0.35	0.29	0.24	0.47	0.70	0.80

4.4.4 Comparison of reservoir inflows from ARIMA forecasts and rating curve.

The generated rating curve for the inlet of the Kainji reservoir is shown below in Figure 53. With a determination coefficient of 0.98, it indicates strong relationship and should yield discharge values that compare well with observed and forecasted inflows from the ARIMA models in Chapter 3.

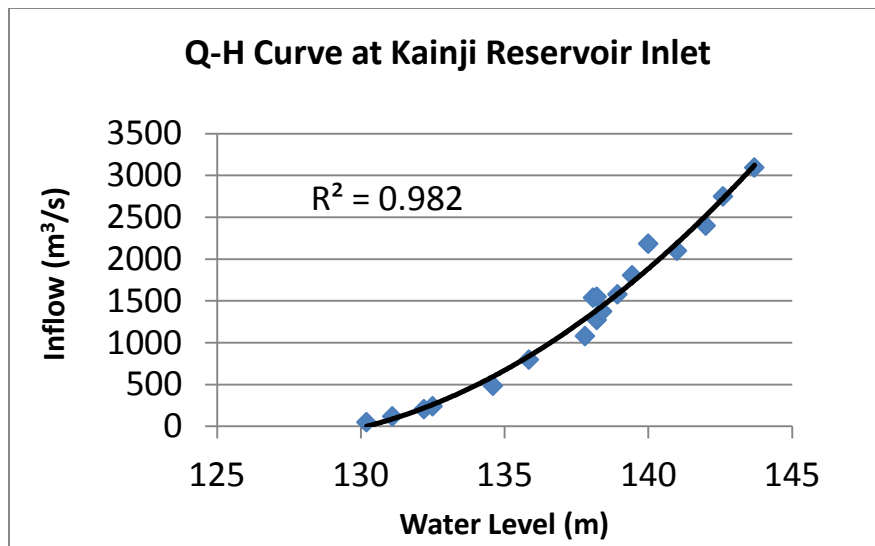


Figure 53: Discharge rating curve for reservoir inlet.

Figure 54 shows a time series comparison of all ARIMA modeled reservoir inflows from Chapter 3 and the inflow estimated from the rating curve (Figure 53) developed using satellite altimetry data. It shows a strong relationship between the different time series until 2007 when altimetric water level collection was discontinued for that location of the Niger River.

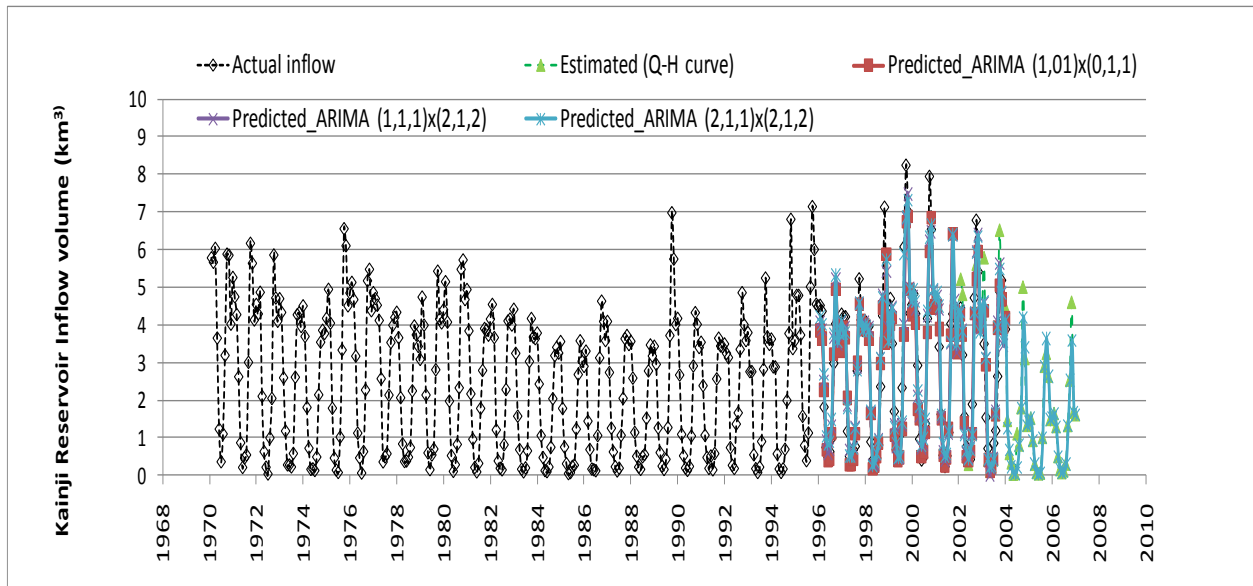


Figure 54: Time series of actual, estimated, and predicted inflows.

4.5 Conclusions

This study shows that altimetry offers great potential for Kainji Lake level monitoring in wet seasons. For dry seasons, altimetric data are still admissible but must be used selectively to complement gage data. Perhaps until the technology improves greatly, wet season altimetric measurements in the Kainji Lake seem more reliable than dry season lake level measurements. Additional research is required to improve understanding of the application of altimetric levels for deriving stage-dependent parameters like reservoir storage, for specific altimeters and seasons. This will increase the overall reliability of altimetry data for reservoir operation and management in the Kainji reservoir.

The validation of forecasted inflows using a discharge rating curve developed from in situ inflows and satellite altimetric levels showed a high relationship between ARIMA modeled inflows from Chapter 3 and those estimated from discharge rating curve developed for the reservoir inlet. This highlights the reliability of the inflow models in chapter 3 and the altimetric level comparison in this chapter. Overall, for the purpose of complementing ground-measured reservoir water level, estimating reservoir inflow, and validating inflows predicted from ARIMA models at the Kainji reservoir, these techniques and results may be used.

CHAPTER 5:

RESEROIR STORAGE VARIATIONS FROM HYDROLOGICAL MASS BALANCE AND SATELLITE RADAR ALTIMETRY

This chapter has been published in the *International Journal of Water Resources and Environmental Engineering* with the following citation:

Salami, Y. and Nnadi F., (2012b), "Reservoir Storage Variations from Hydrological Mass Balance and Satellite Radar Altimetry". *Int. J. Water. Res. Environ. Eng.* Vol 4(6), pp. 201-207.

5.1 Introduction

In order to effectively utilize lakes and reservoirs for such purposes as hydropower generation, irrigation, and flood control, knowledge of water quantity within the reservoir is required. Often, precise values of volume of water available may not be necessary because water surface elevation within the reservoir can be an indication of available storage. This relationship between level and storage, similar to area-volume or level-area relationships makes it possible for engineers to fairly accurately estimate one parameter from the other (Magome et al., 2003). But first, reliable data is required for their computation. In developing countries however, water level and storage data can be difficult to obtain due to financial, maintenance, or administrative issues (Munyaneza et al., 2009). A supplementary solution for water resources management, therefore, would be one that is cost-effective, able to complement conventional technologies, require little human supervision, free of administrative barriers or political interference, and must be demonstrably reliable over long periods and in all kinds of weather. Satellite radar altimeters,

devices used for remotely measuring water surface heights from space, hold immense potentials in this area as demonstrated in seminal studies by Birkett (1994, 1995, and 2000) and Koblinsky et al. (1993). A few more recent studies have demonstrated their application in coastal waters and oceans, but they have also seen some successful use in inland waters (Cretaux & Birkett, 2006).

5.2 Background

This chapter demonstrates the potential of combining validated satellite-measured reservoir level data with ground-measured (gage) hydrological parameters to determine storage variations within reservoirs. Eventually, it shows how reservoir storage may be easily estimated from freely available altimetric water levels measured by satellite altimeters, using a storage-level curve generated from a hydrological mass balance. Many reservoirs in Africa with scarce hydrological data can potentially benefit from this methodology if such reservoirs are amongst the growing global list of reservoirs that are monitored by satellite altimeters. With fairly accurate inflow, outflow, and other hydrological data for a short period only and lake levels from altimeters, storage computations may be performed remotely. In addition, negligible to no changes in the reservoir's geomorphology over time would mean better results, as demonstrated in reservoir storage studies in semi-arid regions like Nigeria (Liebe et al., 2005). Because the Kainji Lake is the largest in Nigeria and one of the longest and largest in Africa by both surface area and volume, its storage variations and general hydrological behavior are vital for national-scale and perhaps continental-scale water monitoring.

5.3 Methodology

5.3.1 Data Collection

Stream discharge data for ten upstream gage locations including at the inflow point to Kainji and Jebba dams were collected. These included daily inflow measurements, in m^3/s , measured by every two hours within the same day then averaged over 24 hours to give a single average daily value. The data range spanned the period from 1970-2003. The data periods available for some of the locations upstream ranged for longer periods, between 1950 and 2003, and for shorter periods, 1979-2003. Each inflow location is reported along with its available data period.

Lake Level Data

Lake level data included satellite-measured and gage measured levels.

5.3.1.1 Altimetric Levels

This study used two separate data sets of altimetry data for the 1992-2002 period:

- (i) Topex/POSEIDON (T/P)
- (ii) ENVISAT

Both sets of altimeter data are freely available online for continental ocean surfaces, and many rivers and reservoirs across the earth surface. Sometimes, they are available in ready-to-use formats with specified units of length.

5.3.1.2 In Situ Levels

Daily and monthly averages of water level within the Kainji reservoir were obtained for the 1970-2002 period from sources at the Kainji Dam Authority in Nigeria. The gages use a reference frame that measures elevation relative to sea level and assumes a single reference point throughout the lake.

Inflows and outflows

Reservoir inflow and outflow data for the Kainji reservoir were obtained for 1970-2003. These included daily inflow measurements and average monthly values, in m³/s. Average monthly values of reservoir inflow and turbine outflow for the 1970-2003 period are presented below in Figure 55 and Figure 56.

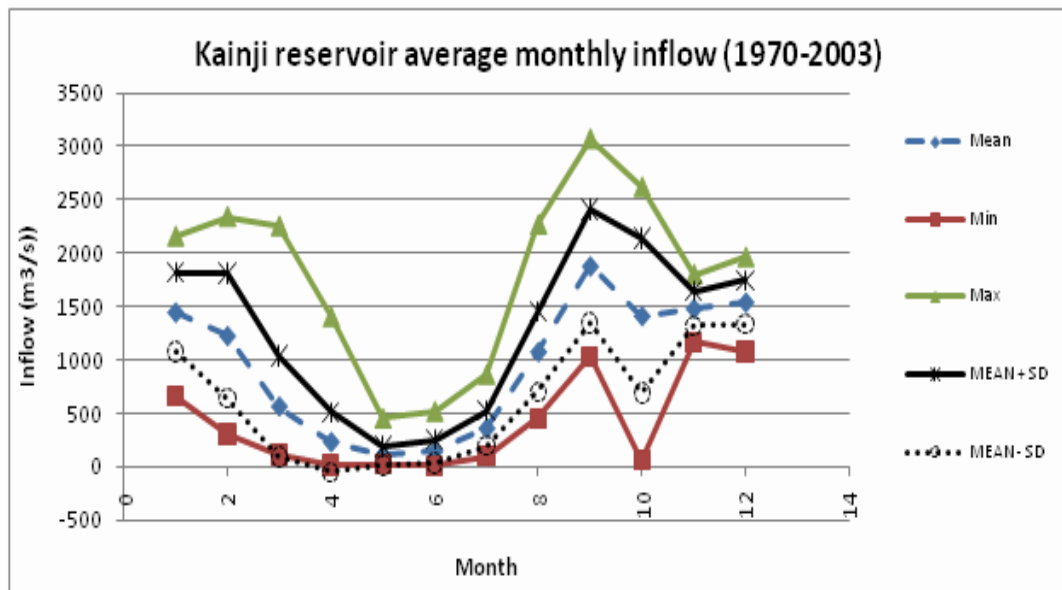


Figure 55: Kainji Reservoir Inflow.

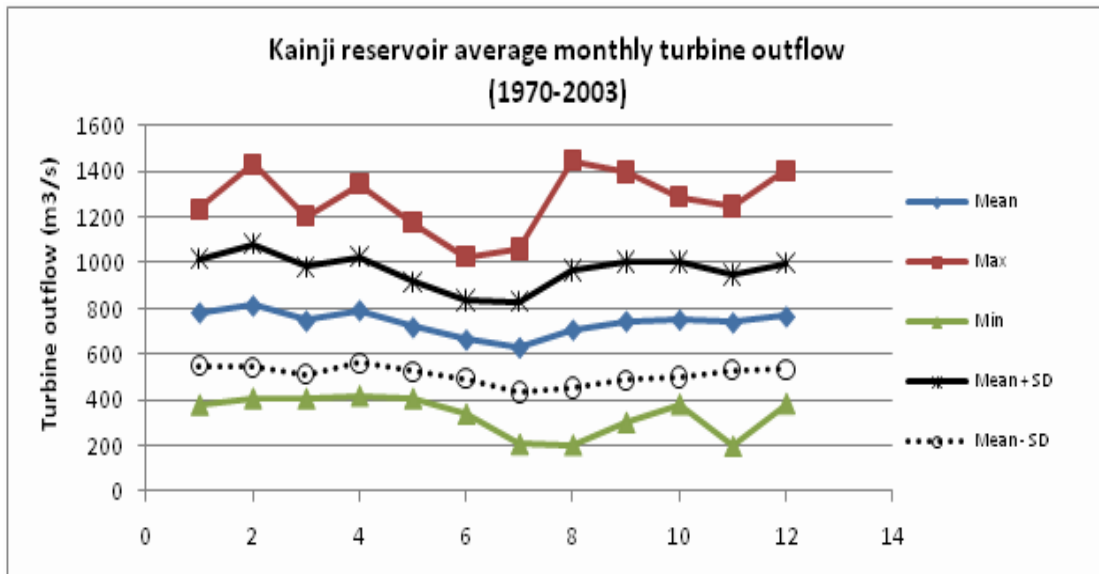


Figure 56: Kainji Reservoir Outflow.

Precipitation

In situ precipitation data for the Kainji reservoir area in Nigeria were collected for 1970 and 2010 (Figure 57). All precipitation data was measured at meteorological stations on site. Supplementary precipitation data based on a global model was also sought for the Kainji reservoir area as an independent medium of comparison. This is climate data-set labeled CRU TS 2.0 prepared by Mitchell et al. (2003). The data is supplied on a 0.5 degree grid, covering the global land surface. The data grid is envisaged as a rectangle with boundaries at the poles and the International Date Line. Data was only supplied for land boxes on the grid, which total 67420. The data is supplied at a monthly time-step for 1901-2000. An extrapolated dataset based a global model is also available for this location for 2011-2020.

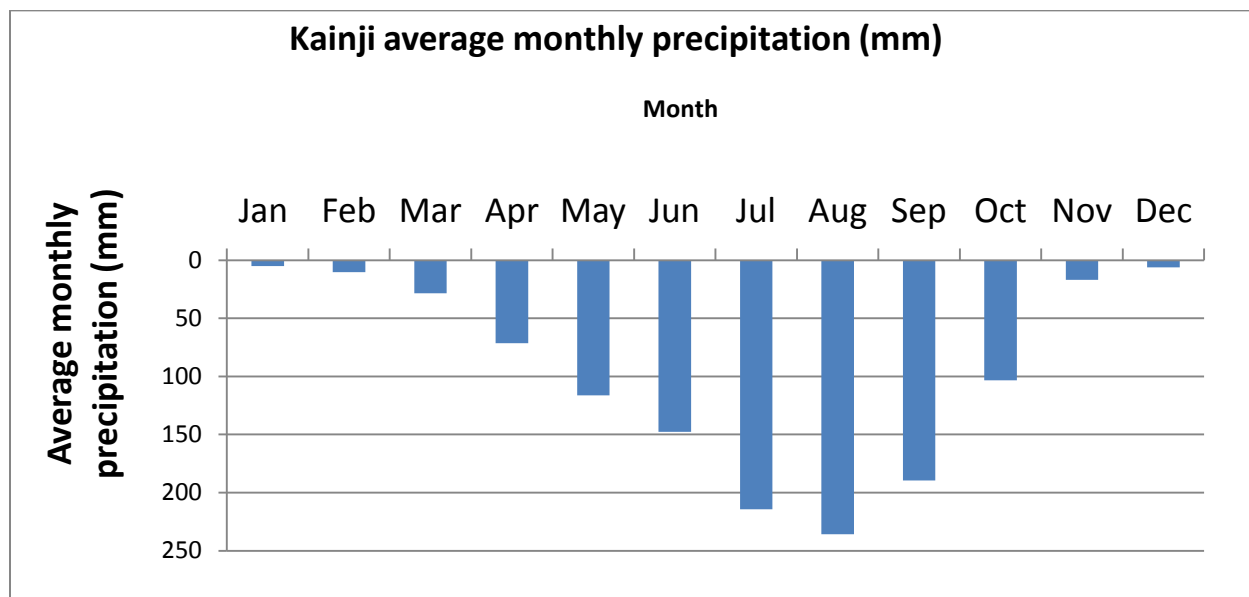


Figure 57: Precipitation over Kainji reservoir.

Evaporation

In situ lake evaporation data for the Kainji Lake was acquired from contacts at Kainji Dam Authority. The data period covered 1980 to 2003. Lake evaporation was also collected for Jebba Lake, south of Kainji Lake. This was to supply evaporation inputs to the intended hydrological mass balance equation for estimating approximate seasonal storage variations in the Kainji Lake. Evaporation was measured by the Class A Pan method at a meteorological observation station which is about 0.6 m away from the reservoir. In accordance with the WMO (1974) method (see MacHattie and Schnelle, 1974), values of pan evaporation were then converted to lake evaporation losses in Mm^3 . Figure 58 shows average lake evaporation over the last 30 years.

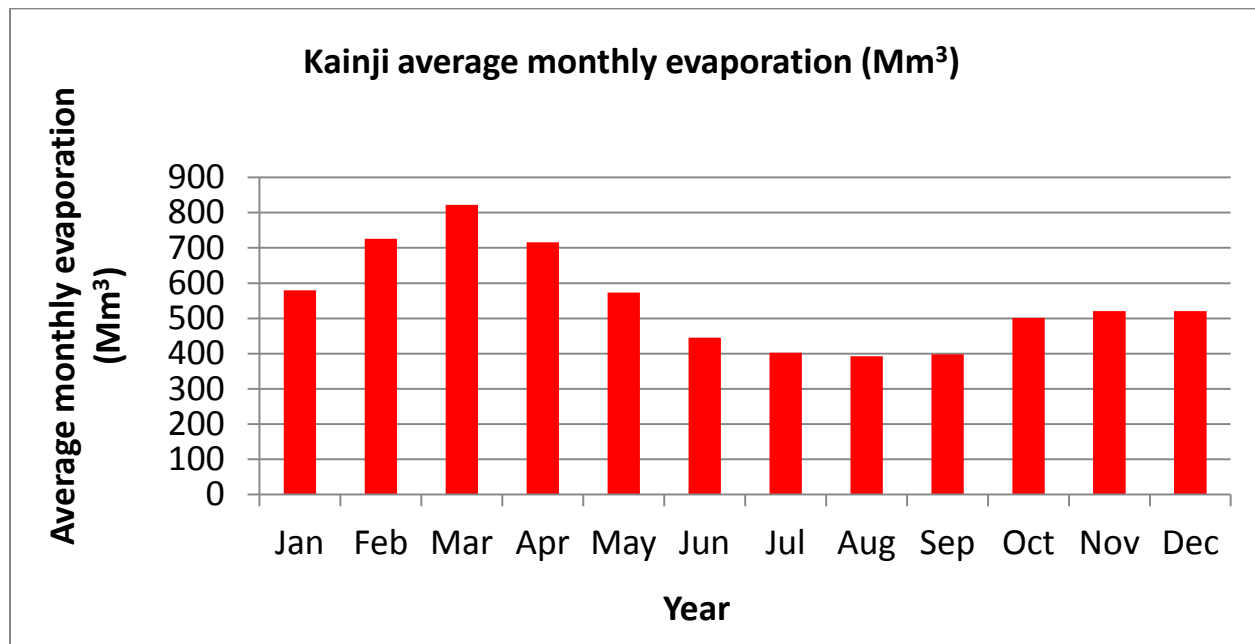


Figure 58: Reservoir Evaporation.

5.3.2 Reservoir Level Validation

Altimetric water levels were validated with gage measured levels to establish the admissibility of altimetry data for storage estimation. The expectation of this task was that a reliably high correlation between ground-measured and satellite-measured water level data would be obtained, therefore suggesting the possibility of replacing scarce lake level data with easily downloadable altimetric depths for the purpose of directly estimating storage from altimetric lake levels. This validation was done by selecting altimetric lake levels measured on the same day as gage levels, to allow for ‘temporal alignment’ of data points measured by different methods. These were then plotted, first to compare ENVISAT and gage levels, then T/P and gage levels. Correlation

coefficients, standard deviation, and root-mean-square (RMS) errors were calculated for each comparison as shown in chapter 4.

Where altimetric product are being used to fill in missing water level data, the altimetry reference frame may need to be the same as the gage reference because the mean height for T/P is just an average, and may not correspond to gage datum or mean sea level datum (Birkett 1995). But where climate change or volume change is of interest, the importance of reference frames become negligible and it suffices to compare relative vertical heights or amplitude variations in the different scales of measurement. In effect, different vertical scales of measurement from different altimeters, if necessary, may be slid up and down to check for coincidence so that while absolute heights or water surface elevations may differ because of different reference frames, relative vertical amplitudes would be identical for the same location (email communication, with Dr. Charon Birkett, ESSIC). In order to homogenize the measurement scales, the original vertical height format of T/P altimetric heights were used directly while both gage and ENVISAT-measured water surface elevations were converted from elevation to relative levels, a scale identical to that used by T/P altimeter. This was done by first plotting T/P altimetric heights against gage water levels and ENVISAT water levels respectively, to obtain a linear plot and equation. The linear regression equation was then used to convert gage and ENVISAT scales to T/P scale. The result of this was a single vertical scale (referred to here as relative water level) by which all three water level data sources were compared. This preference of a single vertical scale that expresses water levels in a positive and negative scale, as used by T/P altimetric data, also allows for an easy comparison of actual water levels

measured using different reference frames. This validation exercise is discussed more extensively by Salami and Nnadi (2012a).

5.3.3 Lake Storage from Hydrological Mass Balance

Abiodun (1973) first suggested the possibility that seasonal storage in the reservoir may be estimated using a hydrological mass balance but mentioned that there were hindrances associated with deciding what parameters to include. In this study, the reasons for the inclusion or elimination of each parameter that would normally be involved in a hydrological mass balance for a lake are explained as follows. First, the volume of water lost to irrigation in dry season is minimal because characteristically low Niger River inflows necessitate control of irrigation use. On the other hand, the rainy season naturally creates availability of water for local farmers, removing the need for excessive irrigation uses in those months. While runoff from the reservoir catchment would be an input to consider normally, catchment contribution around the Kainji accounts for less than 10% of inflow (Onemayin, 2008). That there is very minimal contribution from the catchment between both reservoirs is not a phenomenon unheard of for lakes in moderately dry regions of Africa. For instance while Kainji experiences varied precipitation over the lake area yearly (Oyebande, 1995), Yin and Nicholson (1998) have shown that Lake Victoria in Africa experiences 30% more precipitation over the lake than over its catchment, also suggesting that catchment contribution may be lower in such cases.

Also, the bed of Lake Kainji is of silty alluvium material and it has been shown that infiltration and seepage losses are negligible in reservoirs over fine-textured soils (Talsma and Leiyj, 1976).

Besides, if water balance in the Kainji is examined on a yearly basis, those errors due to infiltration, seepage, and subsequent recharge of surrounding areas become negligible because such lake volumes return to almost the same each year (Sokolov and Chapman, 1974). One exception is that seepage may occur to a limited extent at those parts of the Kainji Lake shore where rocks of the Nupe Formation are exposed. However these are in turn surrounded by impermeable rocks of the Basement-Complex preventing any significant seepage (Nedeco, 1961).

This implies that the significant contributors to hydrological input and output in the lake are reduced to inflow, outflow, precipitation, and evaporation only, and brings the hydrological mass balance equation to the form:

$$\Delta V = (Q_i - Q_o)t + (P - E) = V_1 - V_0$$

where:

t = time interval, $t_1 - t_0$ (in seconds)

If $t_1 - t_0$ is equivalent to one month, then

Q_i = reservoir inflow (m^3/s)

Q_o = reservoir outflow (m^3/s)

P = monthly precipitation volume over the reservoir (m^3)

E = reservoir evaporation (m^3)

ΔV = monthly storage change (m^3)

V_1 = reservoir storage at time t_1 (m^3)

V_0 = reservoir storage at time t_0 (m^3)

Figure 59 illustrates the interplay between the above parameters and the above equation for change in storage fundamentally agrees with that from a study (Obot, 1985) where lake evaporation was the unknown parameter to be determined. By applying this equation, reservoir storage was calculated on a mean monthly basis for each year between 1992 and 2002 as revealed in the time series plot in Figure 60. Level-storage curves were then generated using gage levels, ENVISAT levels, and T/P levels respectively. The storage-level curves (Figure 61) were then used to determine actual reservoir storage using historical reservoir level data.

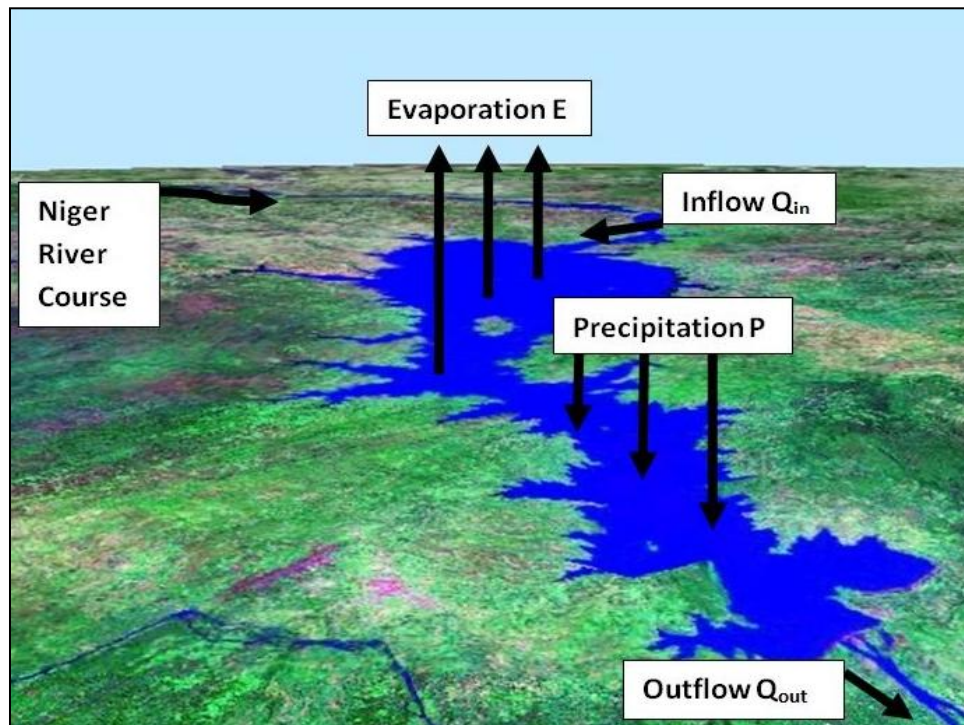


Figure 59: Image of the Kainji reservoir showing main hydrological variables

5.4 Results

5.4.1 Reservoir level validation results

These results were already presented in chapter 4 but are summarized and presented here. Gage vs. T/P level comparison gave a RMS error of 0.54 m while gage vs. ENVISAT comparison gave 0.55 m. These results are consistent with values typical for a lake of this size and have also been previously demonstrated specifically for the Kainji Lake. (Salami and Nnadi, 2012a). It has been shown that the RMS errors vary depending on the size of the lake and the complexity of the contiguous topography (Birkett, 1995).

5.4.2 Reservoir storage results

In Figure 60, the sudden sharp dip and peak in January 1995 and July 1996 respectively were considered outliers in the datasets but included in our analysis. While equipment malfunction in level reading is occasionally responsible, such instances of mild to pronounced variations can be due to sudden significant reservoir releases, or sharp increases in inflow or precipitation in those months. Historical reservoir storage through time as shown below is expressed in cubic kilometers.

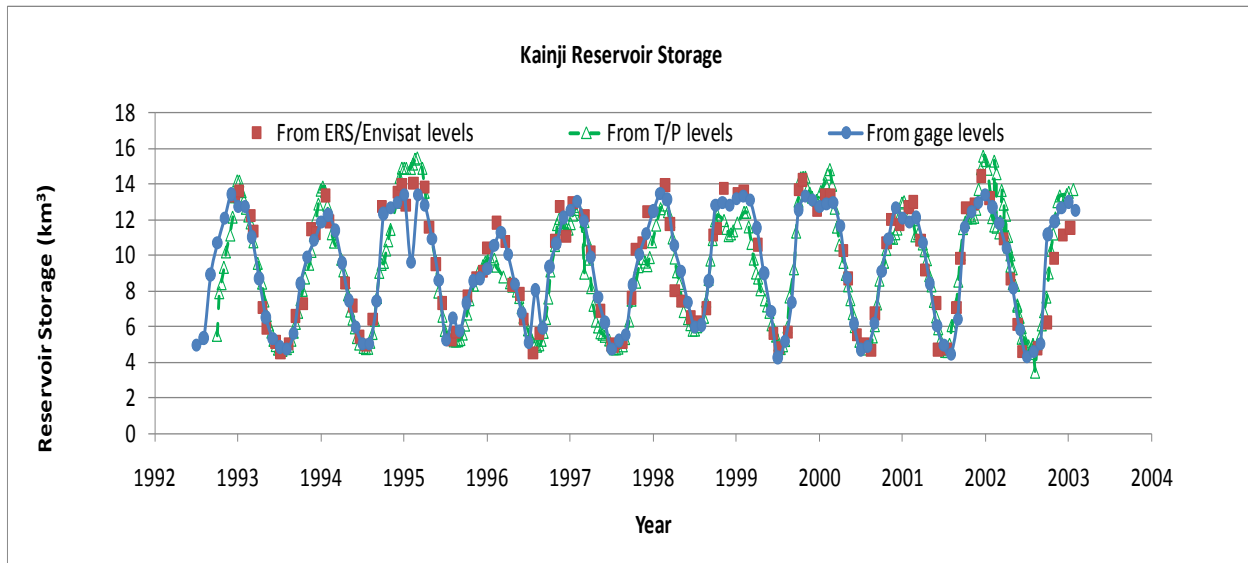


Figure 60: Time series of Kainji reservoir storage derived from in situ, T/P, and ENVISAT levels.

Between 1992-2002, the geomorphology of the Kanji reservoir did not undergo any major changes (Emaobino et al., 2007) due to natural or anthropogenic factors, suggesting that no significant changes in its level-storage curve is expected. To confirm this, biennial level-storage curves generated showed very close similarities between these curves suggesting that a single level-storage curve may be used for the 1992-2002 period and yearly or biennial curves are not necessary. As shown in Figure 61, the level-storage curves for all five years (1993, 1995, 1997, 1999, and 2001) are identical, except for two outliers in the rainy season of 1999 assumed to be caused by erroneous hydrological data due to heavy flooding in that year. (Olawepo, 2008).

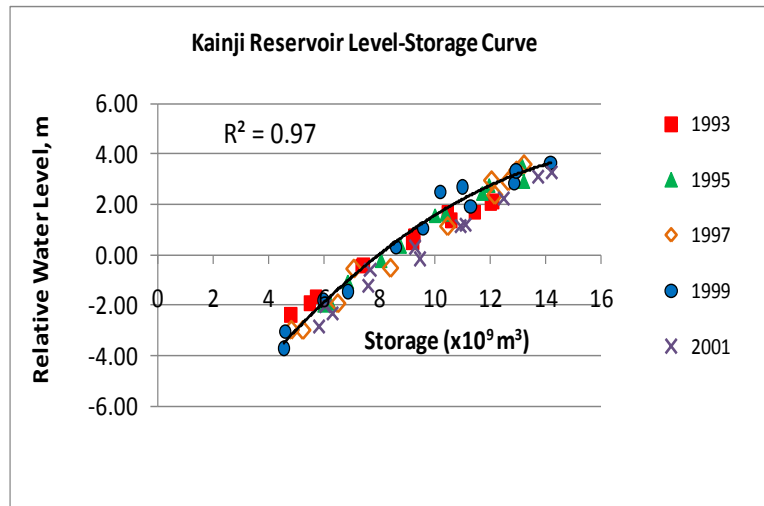


Figure 61: Kainji Reservoir Level-Storage Curve

Using the level-storage curves shown in Figure 61 combined with same-day water level gage measurements, T/P altimeter, and ENVISAT altimeter, Kainji reservoir storage computed for the 1992-2002 period was derived and shown. Comparisons between these are shown in Figure 62, Figure 63 and Table 13.

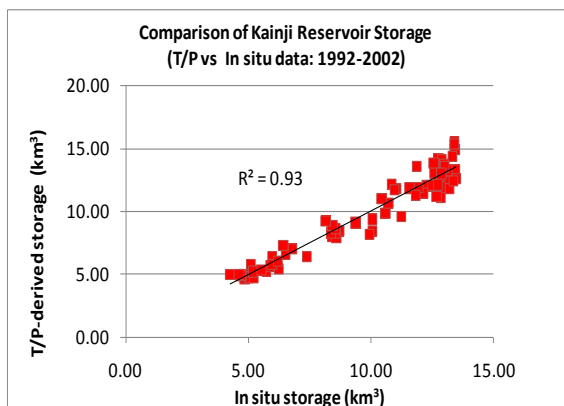


Figure 62: In situ storage vs. T/P-derived storage.

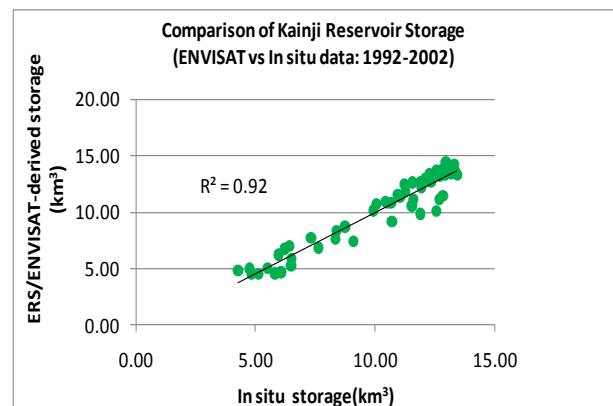


Figure 63: In situ vs. ENVISAT-derived storage

Table 13: Comparison of altimetry-derived storage and in situ storage

	Results of derived storage	
	In situ vs. T/P	In situ vs. ERS/ENVISAT
Average relative error (%)	6.67	7.94
R²	0.93	0.92
RMS Error (km³)	0.81	0.89

5.5 Conclusion

With a RMS error of 0.81 km³ and relative storage error of $\pm 6.67\%$, T/P levels appear to be more useful for Kainji storage estimation, although only marginally. The results of storage derived using both altimetric datasets show that ENVISAT levels are also adequate for storage estimation in the absence of in situ data in the Kainji Lake. Overall, the advantage in temporal resolution of T/P over ENVISAT altimeter in Kainji Lake level comparison is as marginal as the spatial resolution advantage of ENVISAT over T/P in derived-storage.

The comparison of water level data from both ground-measured and remotely-sensed sources in this study produced results which showed that altimetric level can complement gage levels at the Kainji reservoir. Also, the ease of computing monthly, seasonal, or annual storage variations was sufficiently demonstrated to the extent that as new hydrological or storage data becomes available, satellite altimetry data can be combined with storage data to allow for historic, current,

or long-term storage computation. Such information can then be used in effective reservoir operation planning, estimation of hydroelectric energy potential, and overall better water resources management. It is hoped that as the accuracy of altimeters improve, so would the correlation between gage and altimetry levels, and perhaps altimetry-derived storage. In each year, in situ reservoir storage was less than 15 km^3 which is the design maximum capacity of the reservoir. A plausible explanation would be loss of reservoir volume from accumulated effects of sedimentation. It should be noted however that while the hydrological mass balance method used here for estimating storage is a fairly good approximation, the results are as good as the empirical data received for inflow, outflow, evaporation, and precipitation. Overall, the convenient application of the methods outlined in this study also depends on the consistency of level-storage curves over time, catchment hydrology, internet access, reservoir capacity, and the homogeneity of lake level data used.

CHAPTER 6:

ANALYSIS AND ESTIMATION OF FLOOD AND SHORTAGE RISKS

This chapter is being written into a journal article to be submitted to: *Journal of Flood Risk Management* under the following title:

Salami, Y. and Nnadi F., (2012) “Analysis and Estimation of Flood and Shortage Risks In Reservoirs Based on Net Inflow Volumes and Storage Deficit”.

6.1 Introduction and Background

Many reservoirs are built to serve multiple purposes with options to choose from, like hydropower generation, flood control, irrigation, water supply, etc. The need to achieve and maintain the requirements for which each reservoir was built can occasionally create conflicting objectives or priorities (Labadie, 2004). A common example of this would be dual-purpose reservoirs built for hydropower generation and flood control. Achieving the flood control objective requires the availability of storage space within the reservoir to accommodate high inflows which could otherwise cause inundation of surrounding catchment areas (Rosenthal and Hart, 1998). This accommodated storage can then be gradually and safely released over time. However, this runs contrary to the hydropower generation objective of the reservoir which requires appreciably high water levels for power generation. As a result, there arises the necessity for delicate seasonal balance between reservoir levels required for flood storage and the hydraulic head needed for hydropower generation.

In order to balance the conflict between hydropower and flood control objectives, a balance between the two is desired (Kundzewicz and Samuels, 1997)

An innovative risk-based approach is necessary to create this balance by apportioning factors separately to describe extents to which each of these two objectives are being met or not met. Such an approach has to directly involve physical parameters of the system like available net inflow and available storage space or deficit. Other examples of risk analysis considerations for dam safety from a water resources management perspective include studies by Moser and Stakhiu (1987), and Dysarz and Napiórkowski (2002).

Figure 64 and Table 14 show information about the various planned or intended structures along the Niger River. A satellite image of the approximate locations of existing dams in the entire area can also be seen on Figure 10. The average water consumption rates, where known, are presented in Table 14 and Table 15. The total sum of consumptions was first used to directly adjust the inflow parameter in the empirical equations for risk factor. Then the consumptions were factored and reapplied to the equation to denote various scenarios of undefined uses.

Table 14: Dams (existing and planned) along the Niger River.

Structure	Location	Active date	Use	Max. Capacity	Water use & loss
Selingue dam	Mali	1982	Hydropower, Irrig	2.2 km ³	0.80 km ³
Sotuba dam	Mali	1929	Irrigation	Variable	0.22 km ³
Markala dam	Mali	1947	Irrigation	Variable	2.71 km ³
Kandadji dam	Niger	2012	Hydropower, Irrig	1.95 km ³	Variable
Tossaye dam	Mali	Intended	Power, irrigation	4.5 km ³	Variable
Djene dam	Mali	Intended	Irrigation	0.4 km ³	N/A
Talo dam	Mali	Intended	Irrigation	0.2 km ³	N/A
Fomidam	Mali	Intended	Power	6.4 km ³	N/A
Kainji dam	Nigeria	1970	Hydropower, flood control	15 km ³	---
Jebba dam	Nigeria	1984	Hydropower, irrigation	3.66 km ³	---



Figure 64: Approximate locations of some dams shown in Table 14.

Table 15: Niger River diversions and other uses (Source: Hydroconsult, Office Du Niger 2006)

<i>Diversions</i>	January	February	March	April	May	June	July	August	Sept	Oct	Nov	Dec	Total
Inflow at Koulikoro	568	380	339	368	444	745	1759	4455	8571	7794	3483	1311	30218
Irrigated agriculture													
Sélingué	2.2	3.9	5.0	5.1	2.8	0.5	0.7	1.7	2.9	4.4	2.8	1.5	33.6
Baguinéda	18	18	18	18	18	18	18	18	18	18	18	18	215
Office du Niger	151	151	167	166	200	218	219	235	321	321	254	160	2562
Controlled submersion schemes (ORM, ORS)	0	0	0	0	0	0	0	230	33	56	53	26	398
Traditional deepwater rice	0	0	0	0	0	0	0	979	140	237	225	97	1678
Evaporation Sélingué	65	66	77	54	39	25	13	16	37	53	62	62	569
Total	236	239	267	243	260	262	251	1480	552	689	615	365	5458
Losses as a % of the inflow	42	63	79	66	59	35	14	33	6	9	18	28	18

6.2 Methodology

An outline of the methodology for risk determination is broken into sections to differentiate one risk type from another. The methodology is given as follows.

6.2.1 Determination of Flood Risks

Flood risk is the ratio of net inflow volume to available space in both reservoirs (or unfilled volume, also referred to here as storage deficit) within the same time. For chronological exactitude, this was assessed on an monthly average basis. The formula is based on a tentative zero outflow assumption to make the numbers more rigorous for computation. This technique allows reservoir managers to perceive this simple ratio as an initial measure of potential water use before outflow is considered. Outflow can then be factored in as desired to reduce the magnitude of the resulting value. This way, the absolute flood risk cannot exceed what is

calculated. It then allows flood risk factor to be minimized during actual reservoir operation by the inclusion of the outflow parameter based upon the operators' decision for release rates.

Risk_{flood} is given by: $R_f = (I - E + P) / ([S_0 - S]_{\text{Kainji}} + \Delta S_{\text{Jebba}})$

Where

R_f = flood risk factor

I = inflow volume (in km³)

E = evaporation (in km³)

P = precipitation (in km³)

S_0 = storage at full capacity (in km³)

S = current storage (in km³)

ΔS_{Jebba} = flood storage at Jebba reservoir

To be able to denote the unitless number R_f as high or low, the above formula was applied to known historical flood years to determine the magnitude of the risk in those years. Outflow was excluded from this equation because of the uncertainty it creates from being a function of turbine discharge, normal releases, and flood control releases when inflows are high. Because actual reservoir storage is used as release, the tentative absence of outflow in the flood risk equation allows reservoir operators the flexibility of decreasing the potential risks by including preferred outflow values in the equation.

Based on empirical evidence gleaned from bi-annual almanac (of internal report by Nigerian Inland Waterways Division, 2010) and from personal communication (with Engr. Ibrahim Baba, Niger River Basin Authority) on the severity of flooding caused by high inflows and releases in the lower Niger River at Kainji between 1983-2004, the following risk factors were determined to indicate various levels of flood risks.

$$1.50 \leq R_f < 2.49 \text{ (low flood risk)}$$

$$2.50 \leq R_f < 3.51 \text{ (medium flood risk)}$$

$$R_f \geq 3.51 \text{ (high flood risk)}$$

A comparison of these recorded flood magnitudes and actual values calculated in this study is presented in the Results section. Flood occurrences with high severity were often recorded at the peak of 'White floods'. Mild and low flood severity mostly arose from sudden releases made to accommodate increasing inflow volumes the beginning of the 'White floods' or during the 'Black floods'. A few negative values of flood risk factors were obtained for months in the dry season when evaporation and outflow greatly exceeds inflow but were taken to be zero for the following reason. Negative values occurred only in dry season when there was decreased precipitation, decreased river flow, and high evaporation rates reflecting a deficit in net availability of water and causing negative values in the numerator of the flood risk equation. Essentially, this indicates negligible to no chance of flooding in those months.

Preliminary application of this methodology yielded some markedly high flood risk factors ($R_f > 3.51$) in the known flood years of 1995, 1998, 1999, 2000, and 2002 suggesting that the adoption of this equation for preliminary assessment of flood risk validates historical data. In fact, in these years, extreme floods did occur that devastated millions of dollars of farmlands and residential areas (Salami and Nnadi, 2012a). The other values ($1.50 \leq R_f < 2.50$) indicate flood risk factors that must still be catered for and can not be disregarded in an exhaustive flood risk management plan. A supplementary analysis of flood risk was also performed using daily inflow time series forecasts. These results based upon monthly forecasts were used to check that the model will reflect flood risks from known flood years and that future flood risks can be assessed on a monthly basis. But applying daily or hourly inflow data will allow for a near real-time prediction of flood risks on a daily basis. For purposes of comparison, tests to estimate the chances of flooding was applied based upon various other existing methodology, like flow duration curves and exceedance probability, and according to Franchini et al. (1996) and Oregon State University stream flow analysis techniques (2005).

6.2.2 Determination of Shortage Risk Factor

Because the objective of shortage risk estimation runs directly inverse to flood risk estimation, the formula applied for use here adopts the same basic relationship.

The risk of water shortage is defined as the inverse of ‘filling potential’ of the reservoir (or ratio of storage deficit at Kainji reservoir to net inflow volume).

Risk_{shortage} is given by: $R_s = (S_0 - S)/(I - O - E + P)$

O = outflow volume, denoted by minimum downstream requirement for power generation. All other terms retain the same meanings.

The inclusion of outflow in the equation expresses shortage risk with minimum outflow demand satisfied. The advantage here is that the formula ensures that shortage risk is defined (as a minimum value) based only on availability of water at the Kainji reservoir since shortage at Kainji reservoir affects Jebba.

To determine flood and shortage risks in projected years, extrapolated precipitation data based on the global model described in chapter 5 and evaporation data based on 50-year average monthly values were used. Storage as estimated by Salami and Nnadi (2012b) were applied to observed years and then average on a monthly basis and extrapolated to future years. Because stream inflow accounts for the most significant proportion of net inflow volumes in the risk equations, the magnitude of any errors expected from using extrapolated evaporation and rainfall would be minimal.

6.2.3 Flow duration curve

This depicts the ability of the basin to provide flows of various magnitudes which are likely to equal or exceed a specified value of interest. Reservoir operation can be based on system's performance within some range of flows, such as flows that occur between 20% and 80% of the time

6.2.4 Exceedance probability

Exceedance probability curves of unregulated river flows reveal how likely the flow exceeds a given value. They are useful in estimating flood-year returns and determining storage allocation and reservoir release patterns. Exceedance probability of inflows to the Kainji reservoir was determined for the observed flow period, and the years of forecasted inflow. A comparison of the trends of these probabilities is presented in the results section.

Exceedance probability $P = m/(n + 1)$

where m is the rank of the inflow value, and n is the total number of inflow data points

6.2.5 Model with Futuristic Upstream Consumption Patterns

Futuristic water consumption patterns must include all kinds and magnitudes of consumption upstream. Significant withdrawals must be accounted for in a new stochastic model of discharge and annual inflow volume reaching the Kainji reservoir. These were computed as percent of monthly inflow to the Kainji reservoir and these factors were applied to the Kainji reservoir monthly inflows and modeled in a new time series analysis.

To illustrate the effects of changing patterns in upstream uses on the time series models of reservoir inflow, flood risks, and shortage risks, the following models and charts are presented.

6.2.6 Examples of hypothetical reservoir inflow scenarios initially considered

In line with the title of this dissertation, several ‘undefined’ inflow and consumption scenarios were adopted to test the hypothetical behavior of the reservoir system using the flood and shortage risk formulae. Recorded upstream water losses by dams and reservoirs, agriculture, evaporation, etc were introduced as constraints to inflow and the corresponding risks determined. Since several other dams are intended and their exact consumption and release rates are undefined, hypothetical scenarios were created to represent these and consequent risk factors were again determined. The following are examples of possible scenarios that were initially tested before the final set of scenarios (Table 16) were decided upon.

Scenario 1: With 20% increase in annual precipitation over Niger republic.

With a hypothetical 20% rainfall increase, this was found to induce an increase in annual inflow volume to 27.85 km^3 . Such a change may then be incorporated into the actual model to see potential effects of shortage risk and flood risk downstream at the Kanji reservoir. Other possible scenarios are as follows.

Scenario 2: With 20% increase in irrigation uses in catchment B only.

It was observed that a 20% increase in irrigation increased upstream irrigation losses to a total of $1.44 \text{ km}^3/\text{year}$ and reduced stream inflow from 29.25 km^3 to 27.81 km^3 . In the actual task, this inflow can then be inputted into the working model to evaluate its effect on reservoir inflow volume over a given period in the future. Risk factors may then be calculated for each month and

a risk management strategy considered from the predicted inflow volumes, by seeking optimum points between flood risk and shortage risk.

Scenario 3: Upon commencement of active use of upstream Kandadji dam

It is estimated that the Kandadji dam, directly upstream of the Kainji dam, will consume an average yearly volume of 4.05 km³ (variable) which equates to 15% losses in current stream inflows at the Kainji reservoir (Zwarts et al., 2005). This is based on design inflows and outflow differences, irrigation uses, and average yearly evaporation and precipitation rates. The completed Kandadji dam model could then be tested to see how downstream inflow volumes are affected.

Hypothetical inflow scenarios used for this study.

The following arbitrary inflow scenarios were the ones actually employed to represent undefined competitive consumption. The model was then re-run to see the effect of these scenarios on the system and the corresponding magnitudes of flood and shortage risks. These scenarios are shown in Table 16.

Table 16: List of all hypothetical consumption and release scenarios

Various simulated scenarios possible from competitive consumption	
Increased inflow scenarios	Reduced inflow scenarios
1 - FLOODRISK (normal inflows)	1 - SHORTAGE RISK (normal inflows)
2 - FLOODRISK with release from EXISTING dams only (+11km ³ /yr)	2 - SHORTAGE RISK (EXISTING dams only: -4km ³)
3 - FLOODRISK with release from ALL dams (+14km ³ /yr)	3 - SHORTAGE RISK (ALL dams: -8.5 km ³ /year)
4 - FLOODRISK (20% inflow increase)	4 - SHORTAGE RISK (10% less inflow volume)
5 - FLOODRISK (40% inflow increase)	5 - SHORTAGE RISK (30% less inflow volume)
6 - FLOODRISK (60% inflow increase)	6 - SHORTAGE RISK (50% less inflow volume)
7 - FLOODRISK (80% inflow increase)	7 - SHORTAGE RISK (75% less inflow volume)
8 - FLOODRISK (100% inflow increase)	8 - SHORTAGE (90% less inflow volume)

To simulate the effect of hypothetical upstream consumptions and releases on observed inflow, yearly consumptions (km³/year) for each dam or group of dams was distributed throughout the whole year using values of mean monthly flow ratio. The mean monthly flow ratio is the quotient of mean monthly flow and annual flow multiplied by 100%. This indicates what percentage of the annual flow occurs in each month of the year. Depending on the type of study, it may then be possible to identify the probable range of flows that need to be considered. When

seasonal aspects of flow at a site are important or when working with more than one site, it is helpful to be able to normalize values for comparison. For purposes of normalization, monthly flow values were taken to be percentages of yearly flow values and applied to the assumed annual inflow decreases or decreases to get monthly inflows.

6.3 Results and Discussion

6.3.1 Flood risks from actual inflows.

The following set of results show flood risk factors calculated using the flood risk equation. The trend of this graph highlights the importance of considering storage deficit and net inflow volume in the evaluation of flood risks.

In Figure 65, a time series progression of monthly inflow volumes and flood risk factor is shown. While high flood risk factors appear to have a correlation with inflow volume for many years, this trend is not consistent throughout. For example, in one of many instances of two successive years where high inflow volumes were recorded (1999 and 2000), the flood risk factor in 2000 was almost 50% lower than in 1999. Figure 66 gives a bar chart presentation of risk factors without inflows. This is explained by the previously mentioned fact that Kainji reservoir typically operators adopt the operational policies of one year for the next year. Going by the flood risk factor equation, similar net inflow volumes would only produce markedly different flood risk factors if the storage deficits are different. Empirically therefore, it is easy to

see that storage deficit was increased in the year 2000 to better accommodate the inflow volumes that year and avoid a repeat of the flooding scenario of 1999. This trend can also be observed in 1994 and 1995, and 2003 and 2004, where the flood risk factor in the previous year is higher than in the next year despite identical inflows.

Similarly, some years (1996 and 1997) with high flood risk factors recorded medium inflow volumes suggesting that flooding in those years were due to high arbitrary reservoir releases, not naturally high stream flows. Often, this occurs right after a year where high inflow volumes were recorded. This trend again suggests that some flooding of the catchments downstream of Kainji and Jebba reservoirs is caused by poor management decisions and release policies at the dams.

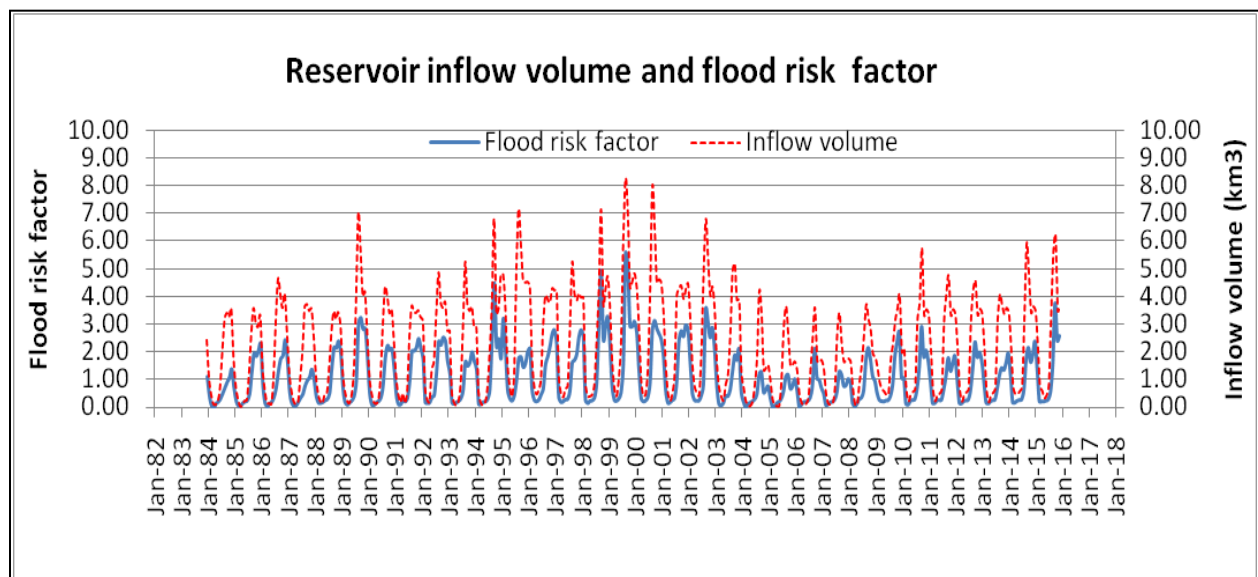


Figure 65: Flood risk factors for actual and forecasted inflow volumes.

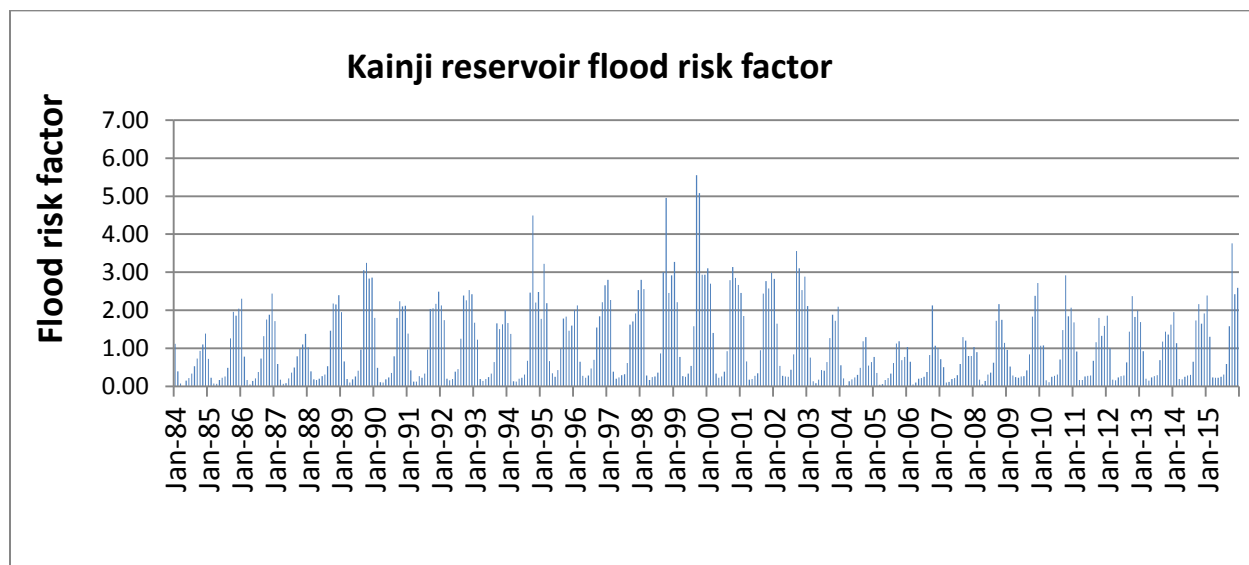


Figure 66: Kainji reservoir flood risk factors (1984-2015).

Based on the flood risk equation and the empirical (flood) severity categorized in

Table 17, the years outlined in

Table 17 and Table 18 were determined as flood years. Except for 2002, the flood years theoretically determined by this study matched actual flood years both for occurrence and severity. The only discrepancy was that the methodology used here determined the 2002 flood to be of medium severity while the flood was recorded to be of high severity, based on area of inundation.

Table 17: Empirical basis of flood risk factor calculation: Reported vs. Calculated (Source: NIWA Internal Report, 2010)

Empirical basis of flood risk classification				
Severity	Reported inundated area (km ²)	Flood years reported officially	Flood years indicated by this study	Flood risk factor
Low	<960	1985-1986, 1988-2003	1985-1986; 1988-2003; 2009-2014	1.5-2.49
Medium	960-2110	1990, 1992, 1993, 1997	1990, 1992, 1993, 1997, 2002, 2010	2.5 - 3.51
High	>2110	1995, 1998, 1999, 2000, 2002,	1995, 1998, 1999, 2000, 2015	>3.51

It must be noted however that the actual flood risk factor calculated for the high inflow period of 2002 was just below the threshold of 3.51 required to fall within the range of a severe flood. So the difference may be considered negligible. The empirical classification of severity is based on decadal internal reports obtained from the National Inland Waterways Division (NIWA) about extent of inundation during flood events. The exact methodology used for determining these inundated areas is unknown but their results matched those from this study 19 times out of 20, the only slight discrepancy between calculated and observed values being in 2002. However, the ‘X’ connotation was maintained in Table 18 to denote flood occurrence only hence its presence in 2002.

Table 18: Empirical basis of flood risk factor calculation

	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Officially reported flood year		X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Flood year from risk factor formula		X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

6.3.2 Flood risk factors from forecasted and hypothetical inflow scenarios

The results of shortage risk factors determined using forecasted inflows and various inflow scenarios are shown below in Figure 67. It shows the expected pronounced effects due to increase in inflow in 2014-2015. The flood risk severity for 2009-2014 is mostly mild. In the statistical summary shown in Table 19, the mean values show only marginal increases from the highest inflow scenario to the lowest inflow scenario.

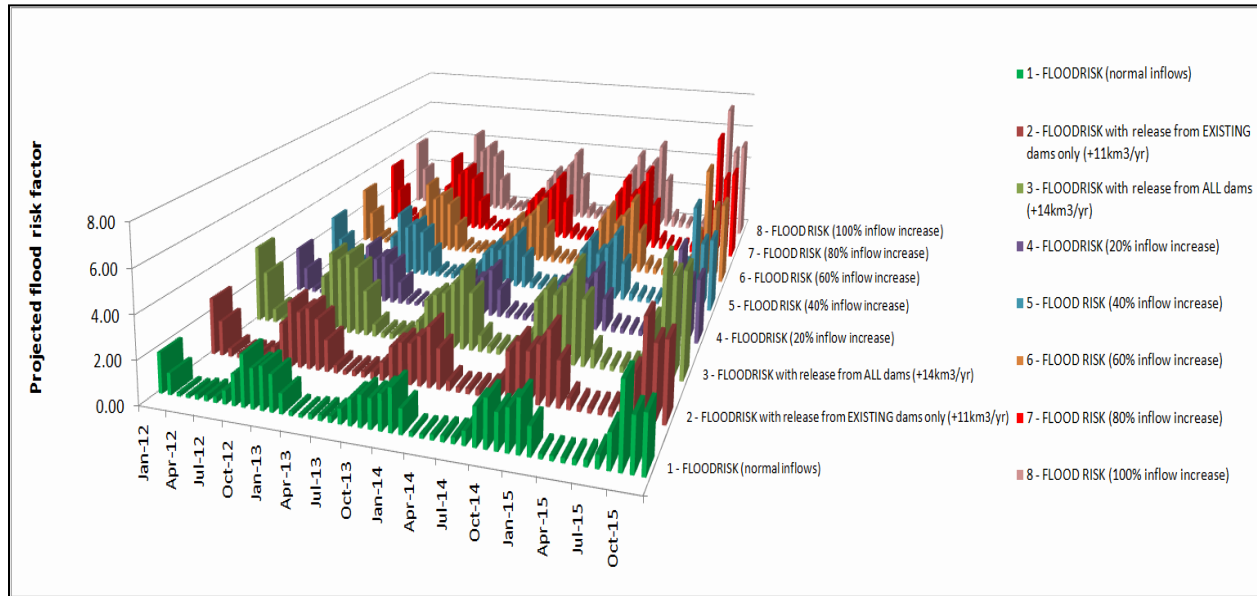


Figure 67: Flood risk factors for various inflow scenarios.

Table 19: Statistical summary of flood risk factors for various inflow scenarios

	1 FLOODRISK (normal inflows)	2 FLOODRISK with release from EXISTING dams only (+11km ³ /yr)	3 FLOODRISK with release from ALL dams (+14km ³ /yr)	4 FLOODRISK (20% inflow increase)	5 FLOOD RISK (40% inflow increase)	6 FLOOD RISK (60% inflow increase)	7 FLOOD RISK (80% inflow increase)	8 FLOOD RISK (100% inflow increase)
Mean	1.05	1.45	1.96	1.25	1.45	1.65	1.85	2.05
Max	3.76	4.54	5.54	4.51	5.26	6.01	6.76	7.51
Min	0.15	0.19	0.25	0.16	0.17	0.17	0.18	0.19
Mean+SD	1.93	2.65	3.58	2.32	2.71	3.10	3.49	3.88
Mean-SD	0.17	0.25	0.34	0.19	0.20	0.21	0.22	0.22
SD	0.88	1.20	1.62	1.07	1.26	1.45	1.64	1.83
Skew	0.82	0.58	0.46	0.81	0.80	0.80	0.79	0.79

6.3.3 Shortage risk factors from actual inflows

Shortage risk factors from observed inflows (1984 – 203) and forecasted inflows (until 2015) are presented below in Figure 68. The results follow the same trend as flood risk factors where the highest risks expectedly occur where demand, in this case, is highest and inflow volumes are lowest. This occurs mostly in the highest points of the dry season between February and June/July. The numerical values of shortage risks exceed flood risk exceed flood risk but these have no direct correlation. An empirical interpretation and analysis of the significance of these values is presented later in this chapter.

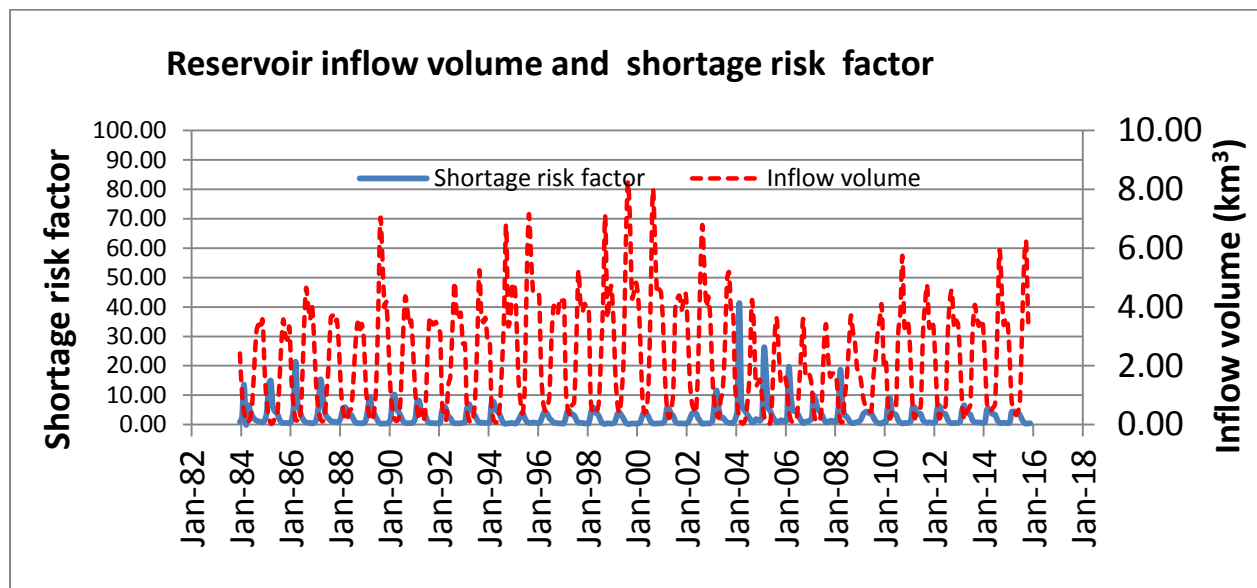


Figure 68: Time series of shortage risk factors and inflows

In Table 20, there is evidence of high correlation (19 times out of 20) between shortage years reported officially by the National Inland Waterways Division and those determined by this

study. Only in the dry season of 1999 was there a discrepancy. This was probably not included in the official report because it occurred only briefly in March 1999 and 1999 was known more as flood year being the year with the worst flooding.

Table 20: Official shortage years compared with shortage years from this study

	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Officially reported shortage year	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X
Shortage year from risk factor formula	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

6.3.4 Shortage risk factors from forecasted and hypothetical inflow scenarios

Shortage risk factors calculated from forecasted inflows and for various inflow scenarios are shown below in Figure 69. There is a proportional increase in the shortage risk factors for scenarios. However, there is a marked difference in the scenarios with 75% and 90% inflow decreases. A situation like this could severely stress the system and cause shortage risks of the severity shown in 2013 and 2014 (See Figure 69). The scenarios which assumed upstream dam withdrawals also reflected increases in shortage risks but to a lesser degree.

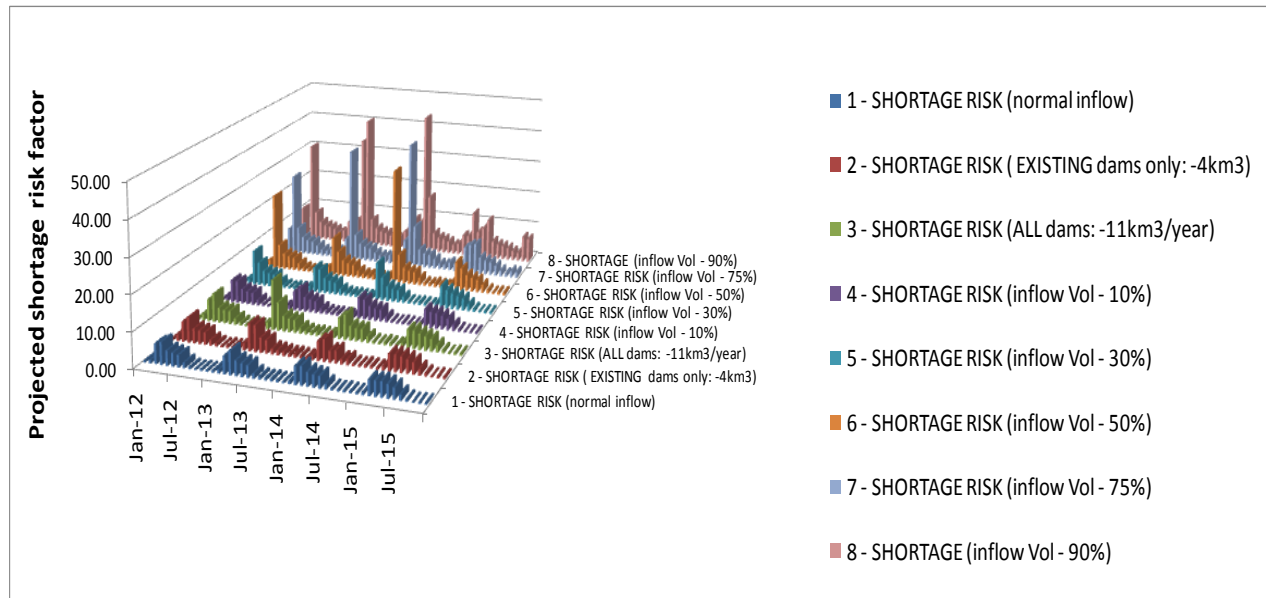


Figure 69: Projected Shortage Risks

Table 21: Statistical summary of shortage risk factors for various inflow scenarios

	1 SHORTAGE RISK FACTOR (normal inflow)	2 SHORTAGE RISK FACTOR (+ EXISTING dams only: -4km3)	3 SHORTAGE RISK FACTOR (with INTENDED AND EXISTING dams: -11km3/year)	4 SHORTAGE RISK FACTOR (inflow Vol - 10%)	5 SHORTAGE RISK FACTOR (inflow Vol - 30%)	6 SHORTAGE RISK FACTOR (inflow Vol - 50%)	7 SHORTAGE RISK RISK (inflow Vol - 75%)	8 SHORTAGE RISK (inflow Vol - 90%)
Mean	2.27	2.50	2.89	2.44	2.92	4.16	5.95	8.69
Max	6.58	7.85	14.46	6.74	11.14	34.50	38.60	43.70
Min	0.27	0.31	0.31	0.30	0.38	0.53	1.05	0.00
Mean+SD	4.21	4.63	5.66	4.53	5.61	10.04	13.54	18.13
Mean-SD	0.32	0.37	0.12	0.34	0.23	-1.73	-1.64	-0.75
SD	1.94	2.13	2.77	2.09	2.69	5.88	7.59	9.44
Skew	0.64	1.03	1.93	0.70	1.32	3.79	3.29	2.70

6.3.5 Flow duration and exceedance probability

By examining historical inflows at the reservoir using flow duration curves for different time periods, the following results were obtained. In Figure 70, the curve for 1970-2003 shows the

entire period for which recorded inflows are available. The curve peaks out at values of flows in excess of $3000 \text{ m}^3/\text{s}$ and an exceedance probability of 0.002. The next period, 1970-1980, was selected because it marks the beginning of the reservoir's existence to the beginning of a period of a decline in inflows in the early 1980s. Moderately lower inflows (about $500 \text{ m}^3/\text{s}$) were mostly non-existent in this period, suggesting that the predominance of these lower inflows occurred mostly in the early 1980s. The reservoir inflow time series plots (Figure 71) show these inflow decreases in the 1980s.

The curve for 2004-2009 shows a curve with markedly reduced inflows. This suggests a reduction in flood risk factor and a possible increase in shortage risk. This is reflected in the forecasted inflow time series (Figure 65). In the 1990s which saw relatively higher inflows, the flow duration curve for 1993-2003 shows increases in the exceedance probability for these high inflows and suggests a correlation between results from the flood risk formula and the flow duration curve. The steepest points of the curves where the highest inflows occurred for 1970-2003 and 1993-2003 have very low exceedance probabilities and are indicative of flash flood occurrences.

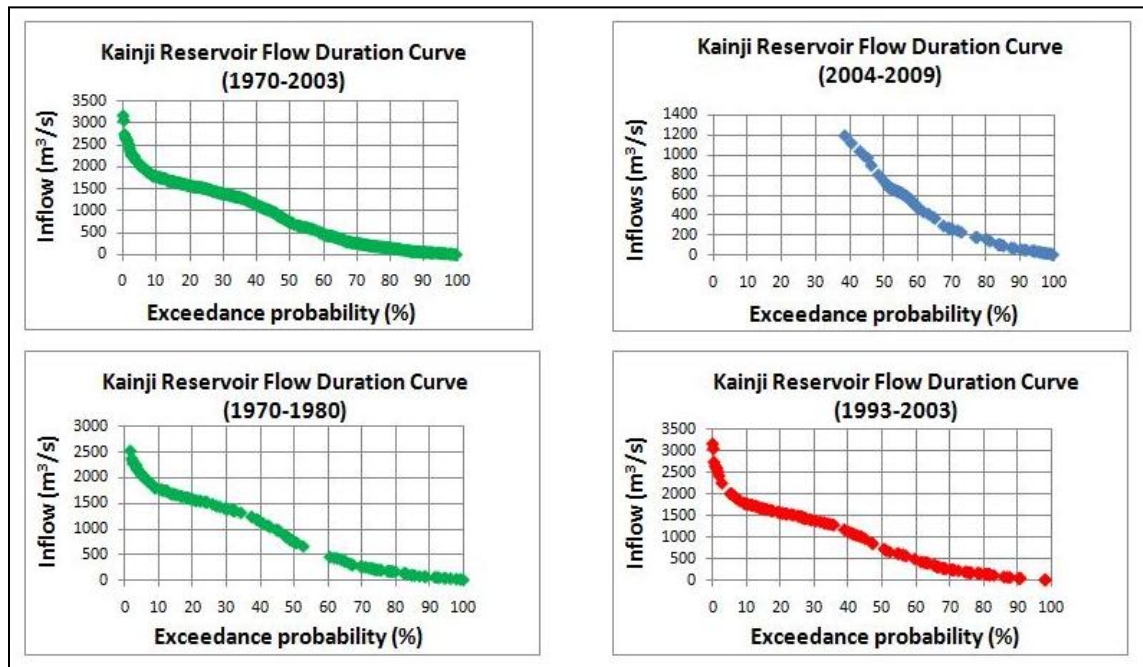


Figure 70: Flow duration curves for Kainji reservoir.

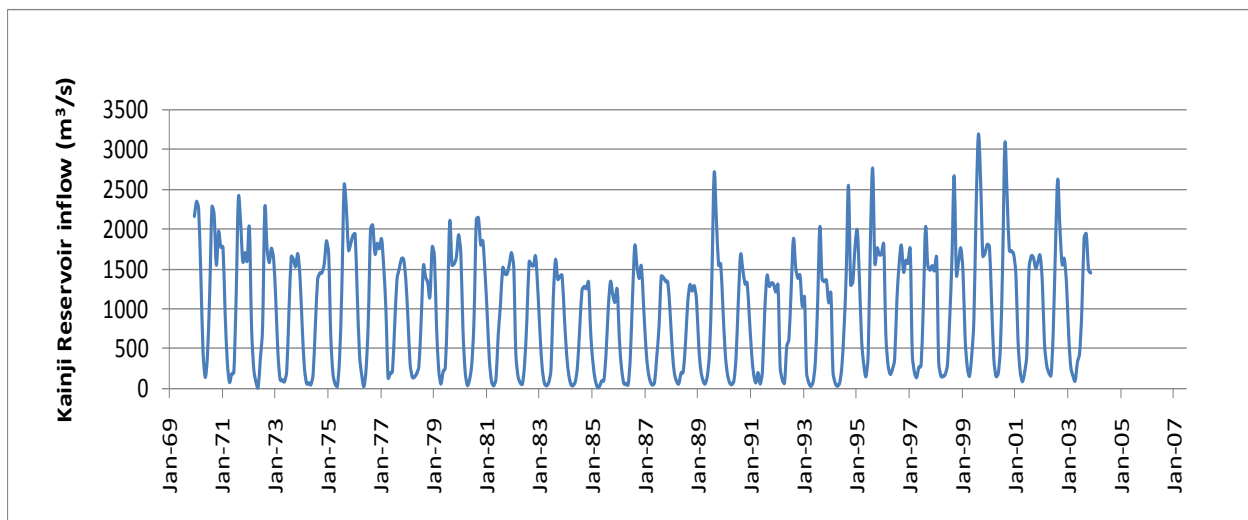


Figure 71: Inflow time series for Kainji reservoir.

6.3.6 Probability Distribution of Inflows

Figure 72 and Figure 73 show Normal and Log-Normal distributions of reservoir inflow volumes (x-axis). These were performed in line with works by Kumaraswamy (1980) using methods specifically for random processes like stream flow. A log-normal distribution better describes the recorded inflow volumes given the number of inflows that fall in the mid-range frequency. The smallest inflows have the highest frequencies. This trend is also evidenced by the exceedance probability curves and explains the long reservoir filling times in dry season indicated by the storage curves in chapter 5. The lower probabilities of higher inflows do not agree with the known incidents of frequent flood occurrence at the reservoir. Again, this underscores the fact that some of the observed flooding is due to human-induced factors and poor management of moderate inflow volumes.

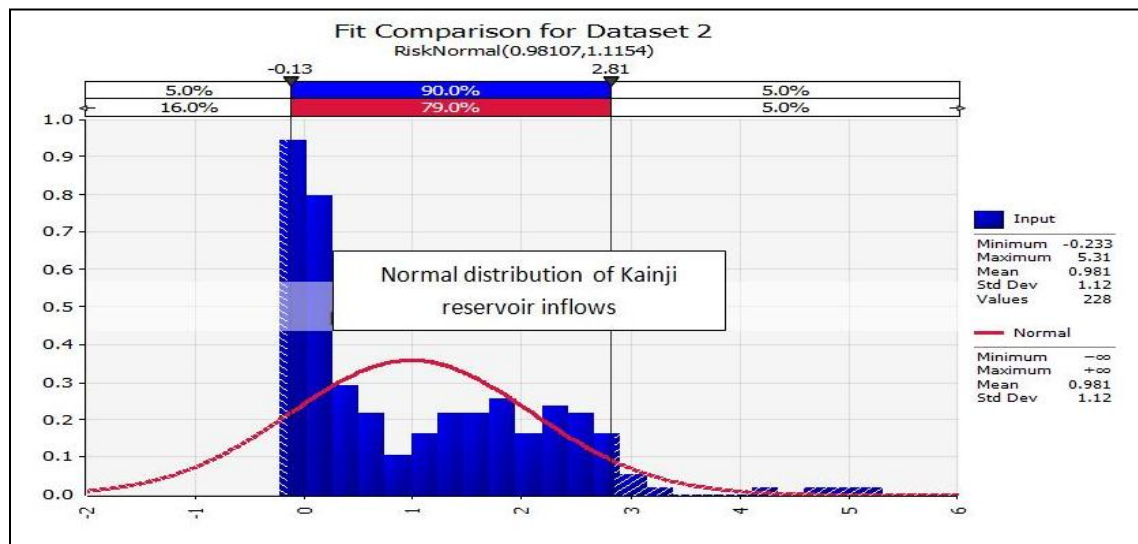


Figure 72: Normal distribution of reservoir inflows

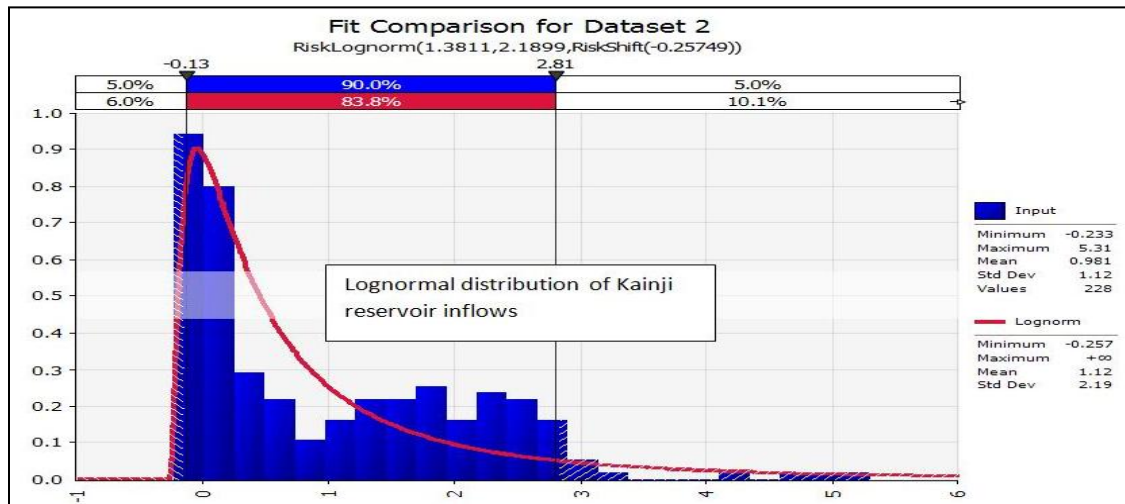


Figure 73: Lognormal distribution of reservoir inflows.

6.4 Conclusions

Results computed from the formulae presented in the methodology section appropriately described flood and shortage risks to this reservoir system for various periods and inflows. These results also compare well with some conventional methodology where only inflows are analyzed to evaluate flood and drought risks. While the magnitudes of flood and shortage risk factors computed for both recorded and forecasted inflow data sets have strong correlations with the actual magnitudes of inflows, there were not always exact. This suggests that risk analysis in reservoir systems with competitive upstream uses and arbitrary release practices must be based upon a comparison of historical and forecasted inflow volumes with typical storage trends. An

approach of this kind would give a broader and more practical representation of the chances of flooding or shortage due to both natural and human-induced factors.

CHAPTER 7:

REDUCTION AND MANAGEMENT OF RISKS

This chapter has been written into a journal article intended for: *Journal of Flood Risk Management* under the following title:

Salami Y., and Nnadi F., “Risk Management in Reservoir Operations in the Context of Undefined Competitive Consumption”.

7.1 Introduction

The process of shortage and flood risk management usually starts in the form of a decision-making process and development of important considerations. During the continuous risk management process, different modes of management can be identified: the pre-flood, the actual flood event for flood management, and the post-flood modes (Rosenthal and Hart, 1998). These terms have also been introduced elsewhere to simplify the systematization of flood risk reduction activities (Kundzewicz and Samuels, 1997). Shortage risk management alternatives can be structured identically, but with considerations to loss and inadequacy rather than excess. According to the comprehensive understanding of flood risk management, the modes also extend to risk analysis and risk assessment. The reduction and management of flood and shortage risks to the Kainji reservoir was the ultimate target of this study. As determined in chapter 6, the magnitude of observed risks and calculated risks match for past years and those for projected years (up to 2015) were explained using inflow volumes and exceedance probabilities.

7.2 Background and Data Collection

In scientific literature, the term risk management can have dual meanings where one involves the inclusion of risk analysis while the other leaves out risk analysis. One foundational concept is based upon the hydrological reliability of existing prophylactic measures and means of risk reduction. In this context, management is expressed as decisions and actions carried out to reduce or lessen the remaining risk beyond flood protection design standards and how much risk remains may then be evaluated by scientific research. Creating a thorough and effective flood risk management techniques in this context would mean first performing flood risk analysis and then, subsequently, devising measures for flood risk management (Marsalek, 1999; Oumeraci, 2004; Hooijer et al., 2004).

The second concept defines management as sets of decisions and actions undertaken in order to analyze, evaluate and possibly reduce flood risks. Portrayed like this, flood risk management covers three phases namely risk analysis, risk assessment and risk reduction (Sayers et al., 2002). These two concepts are actual completely divergent, provide two different options and do not necessarily have to be applied together. The data used in this section to manage projected risk levels are from Chapter 7 where flood and shortage risk factors were determined. These are projected risks up till 2015 based on inflow forecasts and various hypothetical inflow scenarios created to simulate undefined competitive consumption. The risk factors are calculated on a monthly basis.

7.3 Methodology

In order to reduce the magnitudes of flood and shortage risks calculated in the previous objective, it is necessary to first define what constitutes high risk and low risk based on each risk type and value. The actual values of shortage risk factors are numerically higher than flood risk factors.

7.3.1 Criteria for prescribing reservoir releases and storage allocation

(1) Flood risk management (to achieve flood control objective):

$$R_f = (I - E + P - O) / [(S_o - S)_{Kainji} + S_{Jebba}] \leq 1.5$$

where $R_f \leq 1.5$ indicates the maximum permissible risk factor.

(2) Shortage risk management (to achieve power generation objective):

$$R_s = [(S_o - S)_{Kainji} / (I - E + P - O)] \leq 4.5$$

where O = mean required turbine outflow ($750 \text{ m}^3/\text{s}$ or $2 \text{ km}^3/\text{month}$)

To satisfy both objectives above, it was necessary to determine what outflow O and/or storage ΔS will respectively give $R_f \leq 1.5$ and $R_s \leq 4.5$

Both above two criteria may be satisfied by serially solving the simultaneous inequalities in which monthly outflow and storage deficit are the respective unknown values to be determined. Although this task may be automated, the solutions so derived will exist within a broad

boundary. As a preferred alternative, Monte Carlo simulations were used to generate a range of possible reservoir outflows and storage allocations for which both flood and shortage risk criteria are satisfied. The flexibility of using Monte Carlo simulations instead of simultaneous inequalities ensures that exact values of releases and storage requirements that ensure risk reduction are generated, and that these safety values may be easily adjusted as desired by automating the simulations to accommodate changes in inputs.

7.3.2 Steps for reducing flood and shortage risks.

Flood risk management.

- Modify numerator of equation by adding outflow parameter
- Modify denominator of equation by prescribing storage allocation
- Test randomly generated numbers above that give reduced flood risk factor
- What outflow and/or storage will give flood risk factor ≤ 1.5 ?

Shortage risk management

- Adjust numerator of risk equation through efficient storage allocation
- Random generation of safe values of storage deficit to achieve mutually balanced reduction in flood and shortage risk factors
- What outflow and/or storage will give flood risk factor ≤ 4.5 ?

7.4 Monte Carlo Simulation of Undefined Competitive Consumptions

A Monte Carlo simulation is a computerized mathematical technique that helps account for risks in quantitative analysis and decision making. The simulation furnishes the decision-maker with a range of possible outcomes and the probabilities that they will occur for any choice of action. It also shows the most extreme possibilities along with all possible consequences for middle-of-the-road decisions. Monte Carlo simulations can assess the impact of risk, allowing for better decision making under uncertainty.

Dedicated software can be used or the process can be set up in Microsoft Excel. Here, Excel's built-in features, the command RAND and transformations of RAND, were used to provide random values for the uncertain inputs. Microsoft Excel's Data Table command was used to recalculate inputs and collect corresponding output values. To avoid extremely random output values, functional limits were defined for the outputs to fall between. So although the generation of safe reservoir storage levels and outflows was random, their actual values were defined (or controlled) such that the reservoir level could not fall lower than the dead storage nor exceed the maximum capacity. Turbine release was also kept above minimum levels needed for hydropower. Final values fell within limits required to lower the flood and shortage risk factors to safe levels. The output values may be summarized using Excel's descriptive statistics and histogram data analysis tools, or with Excel's worksheet functions and Chart Wizard. But the results from the simulations are presented here in simple series charts showing storage and releases prescribed by the Monte Carlo simulations

7.5 Results and Discussion

Risk management techniques involved applying safe releases and storage allocations to the risk formulae. After the shortage risk and flood risk formulae were modified using safe storage allocations and reservoir releases prescribed Monte Carlo simulations, the result was a marked reduction in the magnitudes of projected risks as shown. In each case, the values dropped below the threshold values for each risk category.

7.5.1 Various simulated storage allocations and reservoir release scenarios for flood and shortage risk management

Figure 74, Figure 75 and Figure 76 all show examples of storage values prescribed by the simulations to help manage the risk levels determined in Chapter 6.

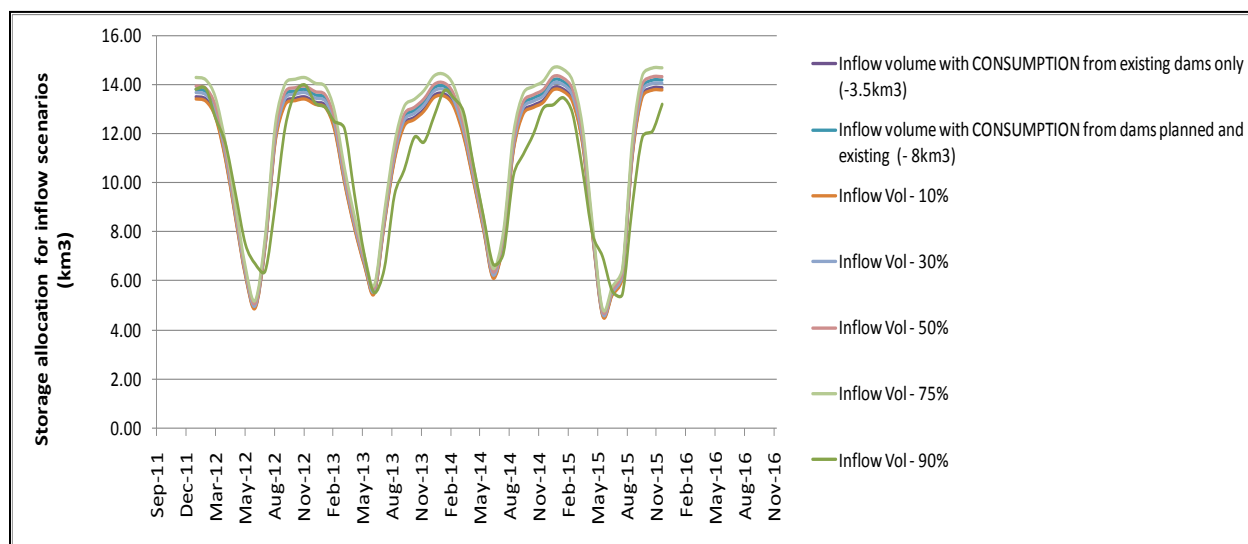


Figure 74: Reservoir storage prescriptions for risk management (Example result of simulation set 1)

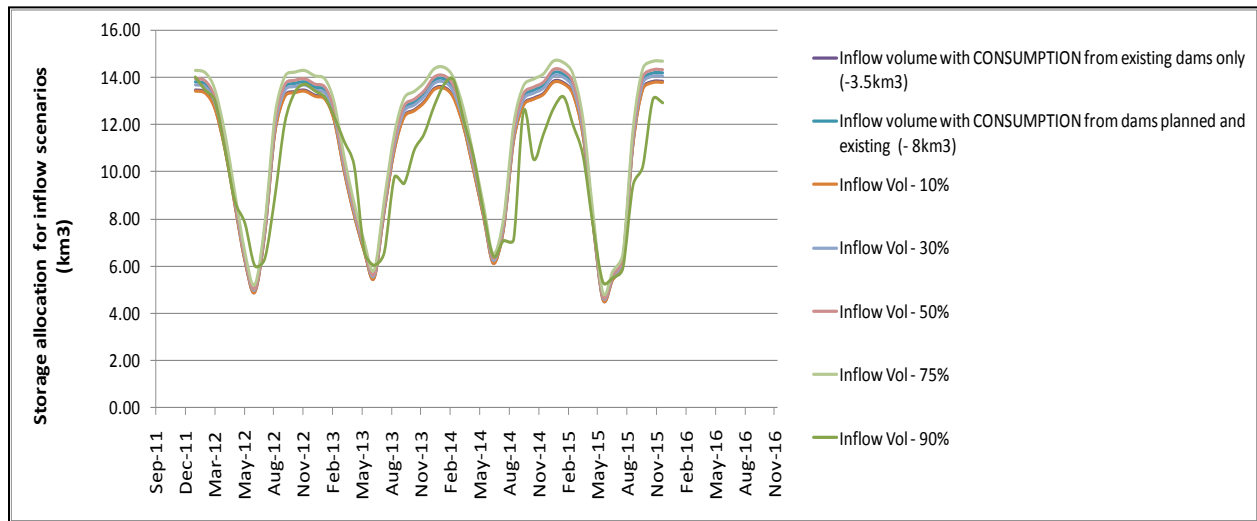


Figure 75: Reservoir storage prescriptions for risk management (Example result of simulation set 2)

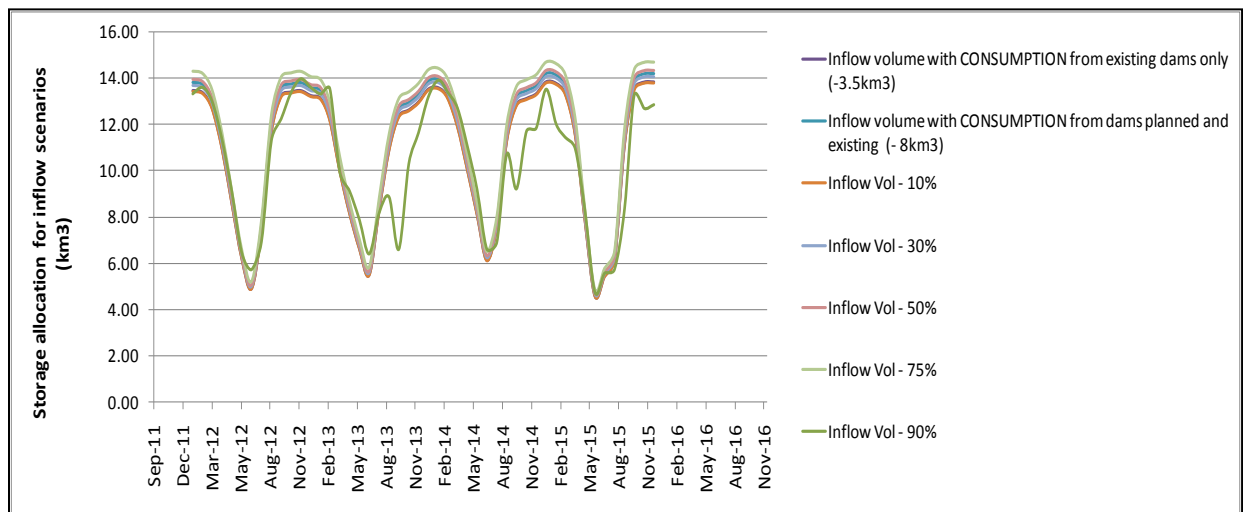


Figure 76: Reservoir storage prescriptions for risk management (Example result of simulation set 3)

The upper and lower limits set for the simulations that generated prescribed storage were proportional across all inflow scenarios except one (90% less inflow). This was done to produce storage values that are not significantly different between inflows scenarios thus yielding optimum values of reduced risk factors, removing the necessity for significant controlled releases, and making reservoir operation easier. The variation in prescribed storage is only significant for the inflow scenario with 90% less inflow. In this case, the recommended trend is an obvious deficit in storage to increase reservoir filling time while allowing the minimum hydraulic head for hydropower generation to be met. The application of controlled limits stabilized the results from the other scenarios so that new simulations must be performed each time fresh sets of values are desired.

Figure 77 and Figure 78 show various outflow scenarios that will help manage risks and reduce the risk factors that resulted from various hypothetical scenarios. In Figure 78, the Monte Carlo prescribed releases with defined limits appear to give a more balanced release curve than past outflow trends determined using historical outflow-to-inflow ratios.

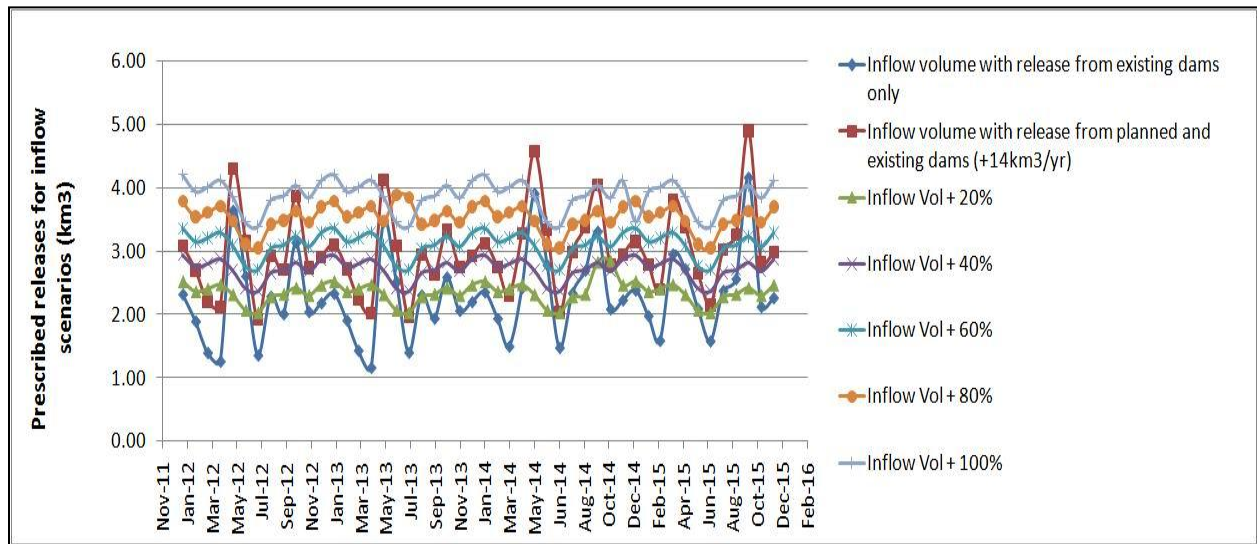


Figure 77: Reservoir outflow prescriptions for risk management

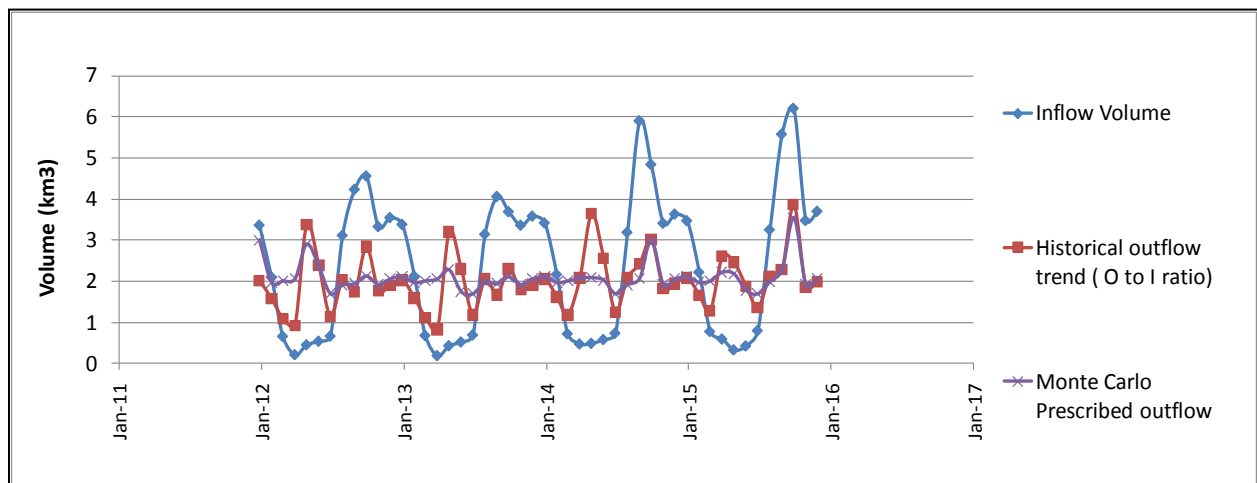


Figure 78: Forecasted inflow compared with outflow situations.

Figure 79 shows a marked reduction in the flood risk factors upon application of the storages and releases prescribed above. All risk factors fell below 1.5 for the years forecasted. Table 22 and Figure 80 show the statistical summary of all reduced risk factors.

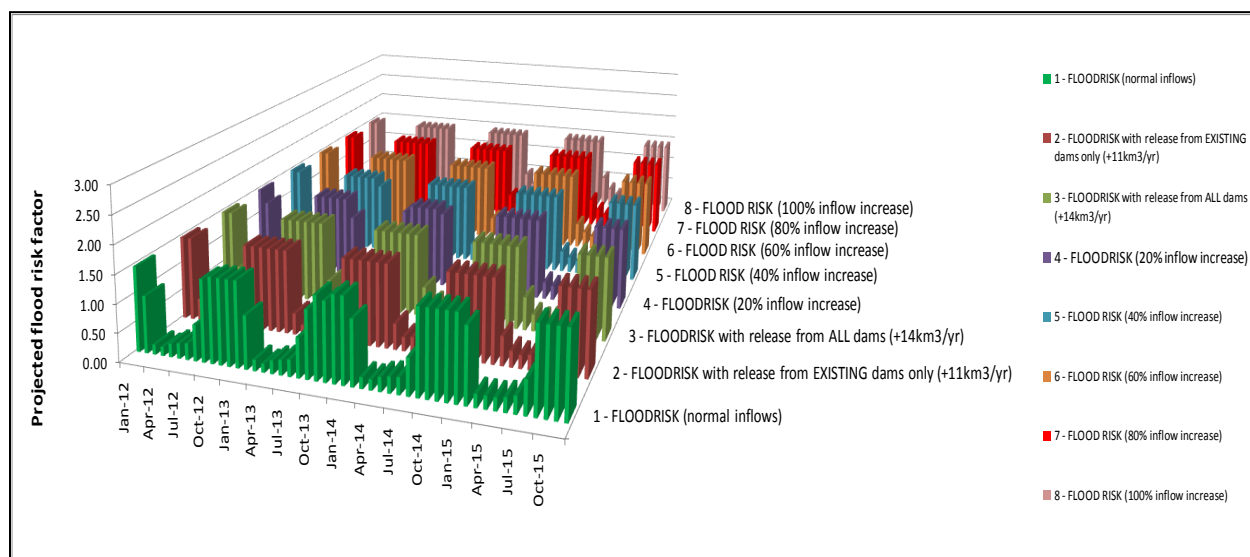


Figure 79: Reduction in projected flood risk factors

Table 22: Statistical summary of reduced flood risk factors.

	1 FLOODRISK (normal inflows)	2 FLOODRISK with release from EXISTING dams only (+11km3/yr)	3 FLOODRISK with release from ALL dams (+14km3/yr)	4 FLOODRISK (20% inflow increase)	5 FLOOD RISK (40% inflow increase)	6 FLOOD RISK (60% inflow increase)	7 FLOOD RISK (80% inflow increase)	8 FLOOD RISK (100% inflow increase)
Mean	0.85	0.94	0.95	0.90	0.93	0.95	0.97	0.98
Max	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49
Min	0.15	0.19	0.20	0.16	0.17	0.17	0.18	0.19
Mean+SD	1.43	1.51	1.52	1.48	1.51	1.52	1.52	1.53
Mean-SD	0.28	0.37	0.39	0.32	0.35	0.38	0.41	0.43
SD	0.58	0.57	0.56	0.58	0.58	0.57	0.56	0.55
Skew	0.01	-0.14	-0.17	-0.09	-0.14	-0.18	-0.23	-0.28

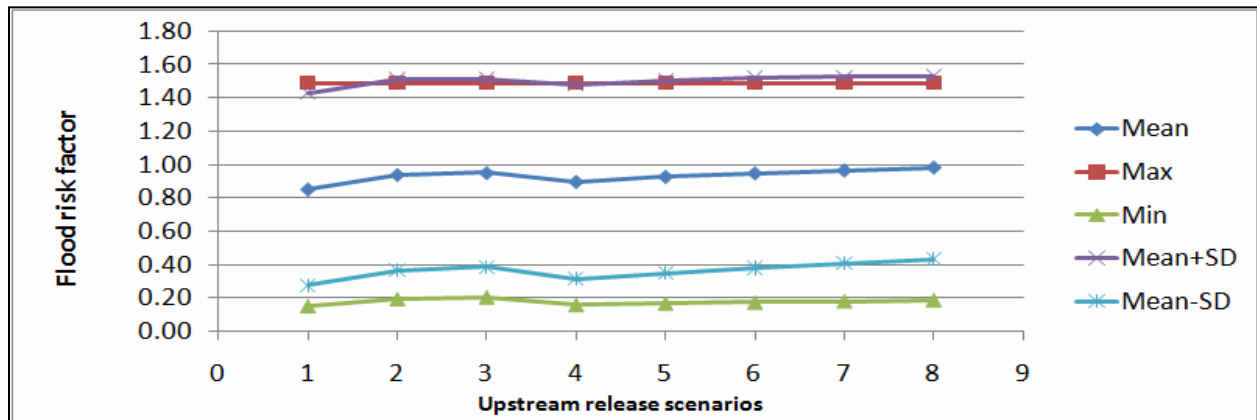


Figure 80: Statistical summary of reduced flood risk factors

Figure 81 shows a marked reduction in shortage risk factors (<4.5) upon the application of the prescribed storage and release scenarios.

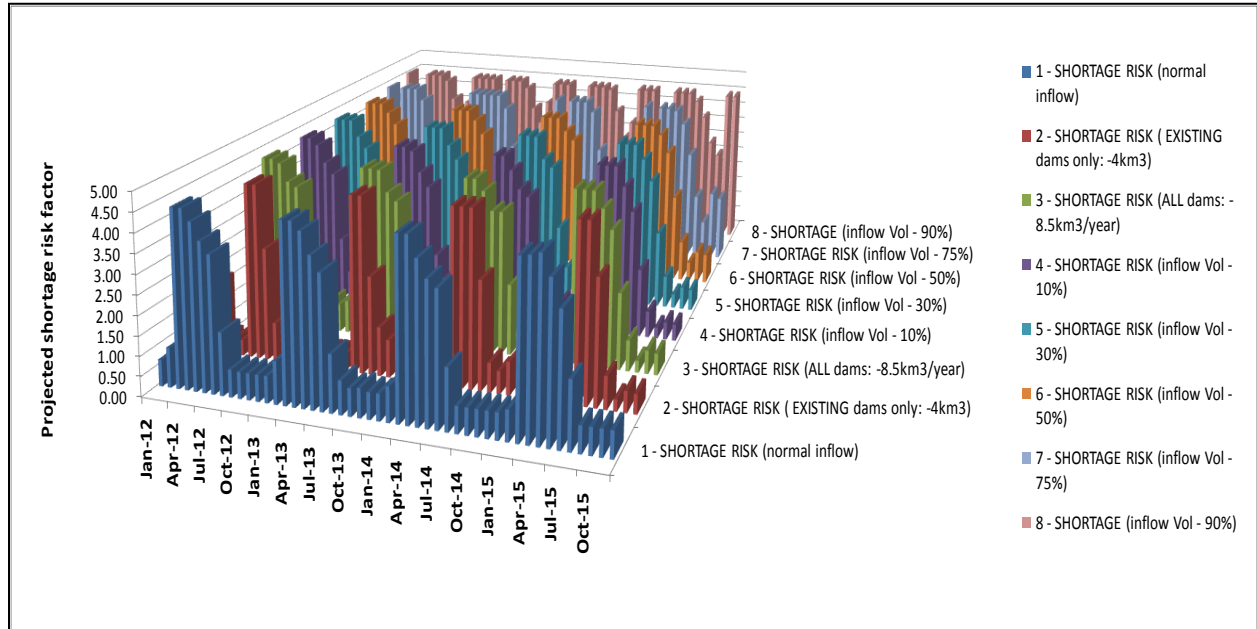


Figure 81: Reduction in shortage risks from forecasted and hypothetical inflow scenarios.

The reduction in shortage risk factors is evident in the statistical summaries in Table 23 and Figure 82. These projected safety levels were achieved using the simulated storage and release values developed to control projected shortage risks.

Table 23: Statistical summary of reduced shortage risk factors.

	SHORTAGE RISK FACTOR	SHORTAGE RISK FACTOR (+ EXISTING dams only: -4km3)	SHORTAGE RISK FACTOR (with INTENDED AND EXISTING dams: - 11km3/year)	SHORTAGE RISK FACTOR (inflow Vol - 10%)	SHORTAGE RISK FACTOR (inflow Vol - 30%)	SHORTAGE RISK FACTOR (inflow Vol - 50%)	SHORTAGE RISK RISK (inflow Vol - 75%)	SHORTAGE RISK (inflow Vol - 90%)
Mean	2.18	1.62	2.36	2.19	2.36	2.62	3.08	3.60
Max	4.49	4.49	4.49	4.49	4.49	4.49	4.49	4.49
Min	0.67	0.31	0.31	0.30	0.38	0.53	0.40	0.40
Mean+SD	3.81	3.17	3.99	3.88	4.00	4.13	4.40	5.03
Mean-SD	0.54	0.06	0.74	0.50	0.72	1.10	1.76	2.16
SD	1.63	1.55	1.63	1.69	1.64	1.52	1.32	1.43
Skew	0.38	1.11	0.24	0.33	0.28	0.15	-0.35	-1.60

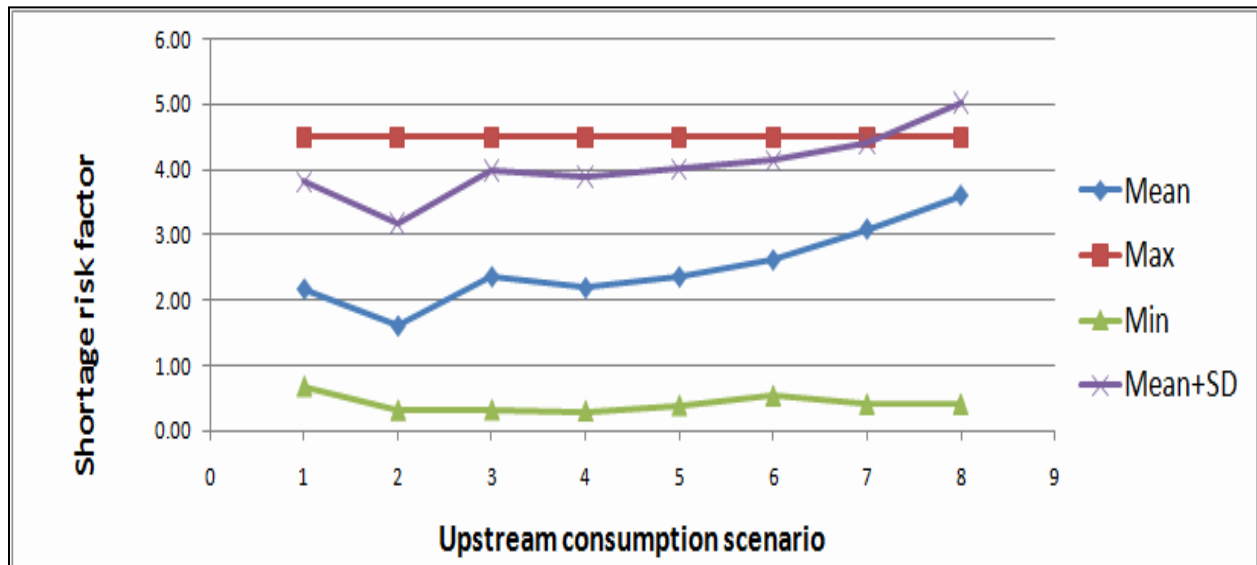


Figure 82: Statistical summary of reduced shortage risk factors

7.6 Conclusions

Overall, the level of reduction in the risk levels to below empirically-determined safe levels shows the flexibility and reliability of this methodology. The reduction in risk factors for observed flood years, if available before their occurrence, could have supplied very useful information on safe releases and storages to maintain for the achievement of both hydropower and flood control objectives. Essentially, this research stands to provide such information in advance to reservoir systems with identical challenges. The ARIMA models on which these forecasts are based must however be periodically re-evaluated and validated as additional in situ inflow data become available. Updated models will make the physical behavior of the system more amenable to inflow forecasting. This will then provide more accurate values of flood and

shortage risk factors which will in turn improve the reliability of the risk reduction techniques presented here.

CHAPTER 8:

RESEARCH SUMMARY AND FUTURE IMPLICATIONS

8.1 Long term implications and possible future research

Given the risk involved in reservoir operation and management, an ever-active topic is that of the potential for flooding and how best to mitigate this. Whether stochastic, risk-based design, deterministic methods, or any other method, the concern about reliability and safety in a hydrologic or hydraulic sense is always an issue among professional engineers. Among the hydrologic topics, statistical multivariate analysis of inflow characteristics is a perceived need.

Research in stochastic terms needs to go beyond flood peak frequency analysis, and explore mathematical models that define risk and scarcity in new ways. While the broad sense of the terms flood risk and scarcity risk stay the same, this study is motivated by the awareness that the field of integrated water resources management needs to explore new methods that analyze, quantify and mitigate these risks by redefining their meanings to suit different contexts, reservoir characteristics, stream hydrology, and catchment characteristics. An overall complicated methodology may be acceptable but a scientific and simplified evaluation of the characteristics of associated risks is more important to allow for applicability in other reservoir systems. The risk-based methods of reservoir operation and management proposed in this study are as simplistic as they are rational.

In summary, it quantifies the availability of the largest feeds and withdrawals (inflow, rainfall, and evaporation) at the reservoir. Then it compares this to available reservoir volume over a

given time period to determine potential flood risk. Tentative exclusion of the outflow term in the equation leaves the decision on release policies to reservoir managers, based on different operational needs. Ultimately, considering release in itself introduces an additional safety factor.

8.2 Final Conclusion

Overall, the key problem for long-term management of reservoirs is balancing conservation and flood control objectives (Valdes and Macro, 1995) and introducing the use of improved forecasts (Stedinger et al., 1995). The basic aim is always to determine the effects of catchment hydrology, conservation characteristics and the operation of multipurpose reservoirs on flood control performance. This dissertation has examined one methodology out of several possible ways to analyze and solve these problems. Other approach may not directly involve inflow forecasting and risk determination but some kind of decision-making medium or model is necessary to fully explore the range of options of solutions available. Lastly, the methodology proposed here offers potentially significant solutions for the longstanding problem of storage reallocation in reservoirs and the provision of fairly good forecasts of a critical hydrological parameter.

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