IMPACTS OF RESERVOIRS ON FLOODS IN KRISHNA RIVER BASIN

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Certificate

This is to certify that the thesis, entitled "***Impacts of Reservoirs on Floods in Krishna River Basin***", being submitted by Mr. Gaurav Kalidas Pakhale to the Indian Institute of Technology, Delhi for the award of Doctor of Philosophy, is a record of bonafide research work carried out by him under our joint supervision. The thesis work, in our opinion, has reached the standard, fulfilling the requirements for the said degree. Further, we certify that this submission is Mr. Gaurav's own work and that, to the best of our knowledge and belief, it contains no material previously published or written by another person which to a substantial extent has been accepted for the award of any other degree or diploma of any University or Institute, except where due acknowledgment has been made in the text.

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Abstract

The role of reservoirs and their operation during times of impending extreme flood events as well as during active events in real time has long been under scrutiny in India as well as globally. The genesis of this debate may be traced to the recurrent post facto experiences that point to likely exacerbation of flood related emergencies and consequent distress situations caused by emergency reservoir releases. These 'panic' releases become inevitable as need arises to resort to emergency responses. It is often averred that, with due diligence, foresight and rational release decisions, such panic responses could have been avoided. The spectre of brimming upstream reservoir storages occurring concurrently with the arrival of extreme levels of flood inflows is indeed an overwhelming influence that only reinforces the latter perceptions.

Interest in the underlying dichotomy between reservoirs as a dependable structural flood mitigation alternative on the one hand and their potential to actually enhance severity of flood risks during active flood events on the other, is comparatively recent. This is notwithstanding the fact that the interest in reservoirs as an effective flood mitigation measure has a long and proven record. However, it is no surprise that studies to develop an objective, case study specific, framework to assess the comprehensive impacts of reservoirs on floods of extreme levels are indeed few and far between.

The Krishna River Basin (KRB) ranks amongst some of the hydrologically most altered river systems in India and is the research focus of this doctoral research. Owing to the basin's significant feature of being both flood- and drought-prone, the scope of the development of water resources through large reservoirs and their extensive socioeconomic reach across the basin is tremendous. The thesis investigates the role of reservoir operation on extreme flood event prognosis along with their design features and the existing operation policies as non-structural measures of aversion, mitigation and management of floods and the related issues of changes in the flood event's associated hydrologic risk levels. The thesis also seeks to incorporate these latter issues to develop insights into possible flood risk management policy framework. This Ph. D. research seeks to understand the role of reservoirs by framing an approach that seeks to score high on a sound rationale and objectivity. This, it is averred, will provide the grounds for a comprehensive spatiotemporal assessment of impacts of reservoirs on various dimensions of floods in the KRB.

Present research follows a step-by-step multidimensional approach to analyse the spatiotemporally diverse impacts of reservoirs on floods of the KRB evaluated through (a) overall water balance of the KRB, (b) site-specific flood frequencies of flood peaks and flood volumes

(c) project specific reservoir operation and flood inundation mapping. Recognising the magnitude of spatial and temporal variation in hydrometeorology and anthropogenic impacts, a previously established categorization system of splitting the basin geographically into 12 sub-systems (K1 to K12), has been adopted in this research and, for each such sub-system, hydrological reconstructions have been carried out of (i) business as usual (regulated) scenario and (ii) virgin, unimpaired (unregulated) scenario using the SWAT hydrological modelling platform. Preliminary studies suggest that a univariate flood peak frequency analysis-based flood typology study is unable to adequately capture the true impact of reservoir operations on flood event hydrographs thus underscoring the role and importance of bivariate /multivariate flood frequency analysis (FFA).

Accordingly, the framework presented in this research for the assessment of impacts of reservoir operations on flood typology and associated risk comprises of the following steps — i) Bivariate copula based FFA performed on unregulated flow regime and incorporating AND, OR and Kendall Return Periods of flood peaks and flood volume. ii) Development of Synthetic Extreme Event Flood Hydrographs (SEFHs) for varying bivariate return periods through various parametric and non-parametric approaches and iii) Simulation of reservoir operations to release the developed SEFHs under varying scenarios and criteria of reservoir and system settings to compare the outcomes of current practice rule curves against various release scenarios generated through the predepletion based operation rules proposed in the current study. Finally, HEC-RAS based hydraulic modelling platform is used to route the derived reservoir outflow hydrographs to evaluate the prospects of moderation in the downstream flood inundation patterns under the proposed rules-based reservoir operations.

The major findings of the study are as follows,

(i) Preliminary analysis suggests that direct utilization of recorded streamflows and rainfall data for reservoir impact assessment in KRB is not feasible due to streamflow regime alteration and non-stationary data.

(ii) The hydrological model of KRB developed in SWAT framework can imitate the present hydrological regime reasonably well. NSE values above 0.5 were obtained in both calibration and validation phases.

(iii) A study on flood typology using univariate FFA suggests that the hypothesis of flood events increasing in KRB is untenable, except for the K7 subsystem which shows signs of moderation. However, it should be noted that univariate FFA is not capable of representing the complete characteristics of a flood event. Furthermore, the study found that the return periods of annual maximum flood peaks and the causal rainfall event are significantly different. Therefore, it is not ideal to use rainfall as a substitute for non-stationary streamflow.

(iv) A copula based FFA was carried out on the reconstructed virgin (unregulated) streamflow regime. Results were compared with the observed annual maximum flood peak-volume pairs. The study suggests that subsystems with large reservoir storages (K1, K2, K8, K7, K5) have multiple flood events with similar peak but different volume. On the other hand, subsystems with less storage facilities and short travel time experience flood events with different peaks but having similar volume range (K10, K11 and K12). Additionally, it has been observed that maximum observed flood events fall within the ambit of AND return period curves and not in OR return period curves.

(v) The results of comparison of the design flood estimates of existing projects with copula based FFA suggest that only projects in the K7 subsystem, namely Nagarjuna Sagar and Prakasam Barrage, have their design flood estimates within the range of OR return period curves. In contrast, projects in other subsystems have their design flood estimates around AND return period curves.

(vi) The simulation of various reservoir operation policies for extreme events suggest that predepletion is key in managing flood risk. Based on the Malaprabha reservoir case, which is presented in detail in this thesis, it was observed that a reduction in flood frequencies due to a change in lead time can be as high as 64%. Meanwhile, for the initial reservoir level, it was found to be 79% for the 100-year return period flood.

The key highlight of the present study is the framework designed to assesses the impacts of reservoirs on floods and its application for the case of KRB. Study comes to the firm conclusion that the predepletion-based reservoir operation strategy, if adopted as one of the important non-structural measures of flood management, will ensure robust solutions with better prospects of flood risk mitigation and management in India.

Key words: Krishna River Basin, Hydrological Modelling, Univariate and Bivariate Flood Frequency Analysis, Copulas, Hydraulic Modelling, Synthetic Extreme Event Flood Hydrograph, Reservoir Simulations, Flood Risk Management.

संक्षेप

भाविष्यमे आनेवाली अत्यधिक बाढ को देखते हुए तथा वास्तविक समयमे सक्रिय बाढ के दौरान जलाशयों और उनके संचालन की भूमिका भारत के साथ-साथ विश्व स्तर पर भी लंबे समय से एक बहस का मुद्दा रही है। इस बहस की उत्पत्ति का पता बार-बार सामने आने वाले उन घटनोत्तर अनुभवों से लगाया जा सकता है, जो सम्भवतः आपातकालीन समयमे जलाशयों से पानी छोड़े जाने के कारण तीव्र होने वाली बाढ़ आपात स्थिति और फलस्वरूप / परिणामस्वरूप उत्पन्न होने वाली तनावपूर्ण/ संकटपूर्ण स्थितियों की और इशारा करते हैं । आपातकालीन प्रतिक्रिया की आवश्यकता में इस तरह का 'घबराहट' वाला बहाव अपरिहार्य हो जाता है। अक्सर यह कहा जाता है कि उचित परिश्रम, दूरदर्शिता और तर्कसंगत तरीके से पानी छोड़ने के फैसलों से ऐसी घबराहट वाली प्रतिक्रियाओं से बचा जा सकता है । इस धारणाको यह समझ प्रबल करती हैं की अत्यधिक स्तर के बाढ़ के आगमन के साथ-साथ ऊपरी जलाशयों से होने वाला जल रिसाव वास्तव में एक हतबल कर देनेवाला प्रभाव है।

एक ओर बाढ़ के निराकरण के लिए विश्वसनीय संरचनात्मक विकल्प के रूप में जलाशयों की उपलब्धि तथा दूसरी ओर सक्रिय बाढ़ की घटनाओं के दौरान बाढ़ के जोखिम की गंभीरता को वास्तव में बढ़ाने की सम्भावना, इस अंतर्निहित विरोधाभास में शोधकर्ताओं की रुचि, तुलनात्मक रूप से आधुनिक है, जब की कि बाढ़ से निपटने के प्रभावी उपाय के रूप में जलाशयों में रुचि का एक लंबा और सिद्ध आलेख है। हालांकि, इसमें कोई आश्चर्य की बात नहीं है कि चरम स्तर की बाढ़ पर जलाशयों के व्यापक प्रभाव का आकलन करने के लिए एक वस्तुनिष्ठ तथा विशिष्ट परिस्थिति के अध्ययन पर आधारित ढांचा विकसित करने के लिए वास्तव में बहुत कम ही जाँच हुई है ।

कृष्णा नदी प्रणालि (केआरबी) भारत में जल विज्ञान की दृष्टि से सर्वाधिक परिवर्तित नदी प्रणालियों में से एक है और यह इस विद्यावाचस्पति अनुसंधान का केंद्र बिंदु है। इस प्रणालि की यह महत्वपूर्ण विशेषता है की यह बाढ़ और सूखा दोनों से प्रभावित होनेकी संभावना होती है, इसलिए बड़े जलाशयों के माध्यम से जल संसाधनों का विस्तृत विकास हुआ है तथा नदी प्रणालि में जलाशयों की सामाजिक एवं आर्थिक महत्त्व व्यापक है। यह विद्यावाचस्पति शोधनिबंध तीव्र बाढ़ की परिस्थितियों पर जलशयों के संचालन के प्रभाव का अनुसंधान करता है । इसमें उनके संरचनात्मक वैशिष्ट्य, बाढ़ से बचाव, शमन और प्रबंधन के उपाय के तौर पर उनकी गैर संरचनात्मक मौजूदा संचालन नीतियां तथा बाढ़ की घटना से जुड़े जलवैज्ञानिक जोखिम स्तरों में परिवर्तन के संबंधित मुद्दे भी शामिल हैं । यह विद्यावाचस्पति शोधनिबंध इन मुद्दों को संभावित बाढ़ जोखिम प्रबंधन नीति के ढांचे में शामिल करनेकी अंतर्दृष्टि विकसित करने के लिए भी प्रयास करता है । यह विद्यावाचस्पति अनुसंधान एक ऐसे दृष्टिकोण को तैयार करके जलाशयों की भूमिका को समझने का प्रयास करता है जो ठोस तर्क और निष्पक्षता पर उच्च अंक प्राप्त करना चाहता है। ऐसा अनुमान है कि यह कृष्णा नदी प्रणालि में बाढ़ के विभिन्न आयामों पर जलाशयों के प्रभावों के व्यापक स्थानिक-अस्थायी मूल्यांकन के लिए आधार प्रदान करेगा।

यह अनुसंधान कृष्णा नदी प्रणालि की बाढ़ पर जलाशयों के विविध स्थानिक-अस्थायी प्रभावों का विश्लेषण करने के लिए चरण-दर-चरण बहुआयामी दृष्टिकोण का अनुसरण करता है, जिसका

मूल्यांकन निम्नलिखित के माध्यम से किया गया है - (अ) प्रणालि का समग्र जल संतुलन, (ब) बाढ़ के प्रवाह दर का शिखर तथा बाढ़ की मात्रा की स्थल-विशिष्ट आवृत्ति और (क) परियोजना विशिष्ट जलाशय संचालन और बाढ़ प्रभावित क्षेत्र के विस्तार का नक्शा ।

जल-मौसम विज्ञान और मानवजनित प्रभावों में स्थानिक और लौकिक भिन्नता की मात्रा को पहचानते हुए, इस अनुसंधान में कृष्णा नदी प्रणालि को भौगोलिक रूप से 12 उप-प्रणालियों (K1 से K12) में विभाजित करने की एक पहले से स्थापित वर्गीकरण प्रणाली को अपनाया गया है। प्रत्येक उप-प्रणाली के लिए, SWAT हाइड्रोलॉजिकल मॉडलिंग प्लेटफॉर्म का उपयोग करके (i) सामान्य रूप से व्यवसाय (विनियमित) परिदृश्य और (ii) अप्रभावित (अनियमित) परिदृश्य से जलविज्ञान को ढाँचा गया है। प्रारंभिक अध्ययनों से पता चलता है कि केवल बाढ़ के प्रवाह दर के शिखर की आवृत्ति के विश्लेषण पर आधारित बाढ़ वर्गीकरण जलाशय संचालन के बाढ़ निर्वहन आलेख पर वास्तविक प्रभाव को पर्याप्त रूप से आँकनेमें असमर्थ है। इसलिए बाढ़ आवृत्ति को एक नहीं बल्कि दो या अधिक आयामोंसे आँकनेकी आवश्यकता अधोरेखित होती है ।

तदनुसार, बाढ़ वर्गीकरण और संबंधित जोखिम पर जलाशय संचालन के प्रभावों के आकलन के लिए इस अनुसंधान में प्रस्तुत रूपरेखा में निम्नलिखित चरण शामिल हैं: १) अनियमित प्रवाह व्यवस्था पर किया गया कोपुला आधारित द्वि-पैमाना बाढ़ आवृत्ति विश्लेषण जिसमें बाढ़ के प्रवाह दर का चरम और बाढ़ की मात्रा के AND, OR और केंडल (Kendall) वापसी अवधि शामिल हैं; २) विभिन्न पैरामीट्रिक और गैर-पैरामीट्रिक दृष्टिकोणों के माध्यम से, बदलते हुए द्विचर (द्वि-पैमाना) वापसी अवधि के लिए सिंथेटिक एक्सट्रीम इवेंट फ्लड हाइड्रोग्राफ (एसईएफएच) का विकास; ३) इस अनुसंधान में प्रस्तावित पूर्व-क्षय आधारित संचालन नियमों के माध्यम से उत्पन्न विभिन्न रिसाव परिदृश्यों के खिलाफ वर्तमान नियमोंके परिणामों की तुलना करने के लिए जलाशय और प्रणालि परिस्थिति के विभिन्न परिदृश्यों और मानदंडों के तहत विकसित एसईएफएच को रिसाव करने के लिए जलाशय संचालन का अनुकरण । अंत में, HEC-RAS आधारित हाइड्रोलिक मॉडलिंग प्लेटफॉर्म का उपयोग करके उर्ध्वलिखित प्रकारसे पाए गए विभिन्न रिसाव परिदृश्यों को क्रमित करके, इस अनुसंधान में प्रस्तावित पूर्व-क्षय आधारित संचालन नियमों के माध्यम से उत्पन्न विभिन्न रिसाव परिदृश्यों की प्रस्तावित नियम-आधारित जलाशय संचालन के तहत प्रवाहित बाढ़ से प्रभावित होनेवाले क्षेत्र के विस्तार में शमन की क्षमताओं का मूल्यांकन किया गया है ।

इस अनुसंधान के प्रमुख निष्कर्ष इस प्रकार हैं

(१) प्रारंभिक विश्लेषण से पता चलता है कि कृष्णा नदी प्रणालि के लिए अब तक दर्ज किए गए नदी प्रवाह और वर्षा विवरण का प्रत्यक्ष उपयोग जलाशय प्रभाव मूल्यांकन में संभव नहीं है । क्योंकि नदी प्रवाह व्यवस्था दिनबदिन बदल रही है उसका विवरण भी स्थिर नहीं है ।

(२) कृष्णा नदी प्रणालि की SWAT तंत्र में बनायी गयी जलविज्ञान व्यवस्था वर्तमान जलविज्ञान व्यवस्था का यथोचित अनुकरण करती है। अंशांकन और सत्यापन दोनों चरणों में, एनएसई मानक ०.५ से ऊपर प्राप्त हुआ है ।

(३) एक-पैमाना बाढ़ आवृत्ति विश्लेषण का उपयोग करके किये गए बाढ़ वर्गीकरण अध्ययन से पता चलता है कि कृष्णा नदी प्रणालि में बाढ़ की घटनाओं में वृद्धि की परिकल्पना अपुष्ट

है, विपरीततः K7 उप-प्रणाली बाढ़ की घटनाओं में शमन के संकेत दिखाती है । तथापि, यह ध्यान दिया जाना चाहिए कि एक-पैमाना बाढ़ आवृत्ति विश्लेषण बाढ़ का परिपूर्ण प्रतिनिधित्व करने में सक्षम नहीं है। इसके अलावा, अध्ययन में पाया गया कि वार्षिक अधिकतम बाढ़ के प्रवाह दर के शिखर की वापसी अवधि और बुनियादी वर्षा की वापसी अवधि में काफी अंतर है। इसलिए, अस्थिर नदी प्रवाह विवरण के विकल्प के रूप में वर्षा विवरण का उपयोग करना तर्कसंगत नहीं है।

(४) पुनर्निर्मित (अनियमित) नदी प्रवाह व्यवस्था पर कोपुला आधारित बाढ़ आवृत्ति विश्लेषण किया गया तथा उसकी तुलना वास्तविक दर्ज किये हुए नदी प्रवाह के अधिकतम वार्षिक प्रवाह दर एवं प्रवाह मात्रा के जोड़े के साथ की गई । इस अनुसंधान से पता चलता है कि बड़े जलाशय संचयन वाले उपप्रणालियों में (K1, K2, K8, K7, K5) समान नदी प्रवाह शिखर लेकिन अलग-अलग नदी प्रवाह मात्रा के साथ कई बाढ़ की घटनाएं होती हैं। दूसरी ओर, कम जलाशय संचयन सुविधाओं और कम यात्रा समय वाली उपप्रणालियाँ (K10, K11 और K12) अलग-अलग शिखरों के साथ बाढ़ की घटनाओं का अनुभव करती हैं लेकिन उनकी नदी प्रवाह मात्रा लगभग समान होती है। इसके अतिरिक्त, यह देखा गया है कि अधिकतम देखी गई बाढ़ की घटनाएं AND रिटर्न पीरियड कर्व्स (वापसी अवधि आलेख) के दायरे में आती हैं, न कि OR रिटर्न पीरियड कर्व्स के दायरे में।

(५) कोपुला आधारित बाढ़ आवृत्ति विश्लेषण के साथ मौजूदा जलाशयोंकी परियोजनाओं के नियत बाढ़ अनुमानों की तुलना के परिणाम बताते हैं कि केवल K7 उपप्रणाली के जलाशय (नागार्जुन सागर और प्रकाशम बैराज) परियोजनाओं के नियत बाढ़ अनुमान OR वापसी अवधि वक्रों की सीमा के भीतर हैं। इसके विपरीत, अन्य उपप्रणालियों में परियोजनाओं का नियत बाढ़ अनुमान AND वापसी अवधि वक्रों के आसपास होता है।

(६) अत्यधिक बाढ घटनाओं के लिए विभिन्न जलाशय संचालन नीतियों के अनुकरण से पता चलता है कि बाढ़ जोखिम के प्रबंधन में पूर्वक्षरण महत्वपूर्ण है। मलप्रभा जलाशय के मामले में, जिसे इस अनुसंधान में विस्तार से प्रस्तुत किया गया है, यह देखा गया कि अग्रिम काल में बदलाव के कारण बाढ़ की आवृत्ति में ६४ % तक की कमी हो सकती है। उसी तरह, प्रारंभिक जलाशय स्तर के बदलाव के कारण, १०० साल की वापसी अवधि की बाढ़ की आवृत्ति ७९% तक की कमी हो सकती है।

वर्तमान अनुसंधान का मुख्य आकर्षण बाढ़ पर जलाशयों के प्रभाव का आकलन करने के लिए बनाया गया ढांचा और कृष्णा नदी प्रणालि के मामले में इसके अनुप्रयोग है। यह अनुसंधान इस ठोस निष्कर्ष पर पहुंचा है कि यदि बाढ़ प्रबंधन के महत्वपूर्ण गैर-संरचनात्मक उपायों में से एक के रूप में पूर्व-क्षय-आधारित जलाशय संचालन रणनीति को अपनाया जाता है, तो भारत में बाढ़ जोखिम शमन और प्रबंधन की बेहतर संभावनाओं के साथ मजबूत समाधान सुनिश्चित होंगे।

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Abbreviations

1D:	one-dimensional
2D:	two-dimensional
AMC:	Antecedent Moisture Condition
AMS:	Annual Maximum Series
ANN:	Artificial Neural Network
BCM:	billion cubic metres
cumec:	cubic meter per second
cusec:	cubic feet per second
CWC:	Central Water Commission
DEM:	Digital Elevation Model
DRIP:	Dam Rehabilitation and Improvement Project
FFA	Flood Frequency Analysis
FRL:	Full Reservoir Level
HEC-RAS:	Hydrologic Engineering Centre's River Analysis System
HEP:	Hydro-Electric Project
HFL:	Highest Flood Level
HO:	Hydrological Observation
IHA:	Indicators of hydrologic Alterations
IMD:	India Meteorological Department
IWMI:	International Water Management Institute
km:	Kilometres
KRB:	Krishna River Basin
KWDT:	Krishna Water Disputes Tribunal
m:	meters

MAF:	Mean Annual Flow
MMF:	Mean Monthly Flow
MPL:	Minimum Pool Level
MWL:	Maximum Water Level
Qp:	Peak flood discharge
RP:	Return Period
RVA:	Range of Variability Approach
SEFH:	Synthetic Extreme Event Flood Hydrograph
sq. km.:	Square Kilometres
sq. m.:	Square Meters
SRTM:	Shuttle Radar Topographic Mission
SWAT:	Soil and Water Assessment Tool
TMC:	Thousand Million Cubic Feet
Tp:	Time to Peak
USGS:	United States Geological Survey
V:	Volume