

**DECISION-MAKING UNDER DEEP UNCERTAINTY MODELLING
FRAMEWORK FOR ROBUST WATER RESOURCE MANAGEMENT
IN THE UPPER YAMUNA RIVER BASIN, INDIA**

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FRAMEWORK FOR ROBUST WATER RESOURCE MANAGEMENT
IN THE UPPER YAMUNA RIVER BASIN, INDIA**

by

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Submitted

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CERTIFICATE

This is to certify that the dissertation entitled “**Decision-Making under Deep Uncertainty Modelling Framework for Robust Water Resource Management in the Upper Yamuna River Basin, India**” which is being submitted by Mr. Dinesh Kumar, for the award of the degree of Doctor of Philosophy in Civil Engineering, to the Indian Institute of Technology (IIT) Delhi is a record of Bonafide work carried out by him under my sustained guidance and supervision. The dissertation has reached the standard fulfilling the requirements of the regulations relating to the degree. The results embodied in the dissertation have not been submitted to any other university or institute for the award of any degree or diploma.

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Dedicated to

My **FAMILY** for their unconditional love,

My **TEACHERS** for their invaluable guidance and wisdom,

My **FRIENDS** for their unwavering companionship,

And to **GOD** for endless blessings, strength, and grace.

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ABSTRACT

Water resource management in the Upper Yamuna River Basin (UYRB) faces increasing challenges due to climate change, socio-economic pressures, and governance constraints. Traditional predictive models, which rely on deterministic or probabilistic forecasts, often struggle to address complexities under deep uncertainty. As climate change intensifies and demand grows, ensuring resilient and adaptive water governance in the region requires decision-centric approaches that accommodate multiple plausible futures. This study applies Decision-Making Under Deep Uncertainty (DMDU) to develop robust adaptation pathways, leveraging stakeholder-driven knowledge co-production, physical climate storyline approaches, fit-for-purpose modeling, stress-testing of adaptation options, and developing dynamic adaptation policy pathways.

A co-production framework was developed, incorporating participatory modelling and decision-support tools to create adaptive water management strategies. A transdisciplinary approach facilitated collaboration among policymakers, researchers, and communities, ensuring actionable, context-specific solutions. The XLRM framework structured the analysis by categorizing uncertainties (X), policy levers (L), relationships (R), and performance metrics (M) to evaluate adaptation options. Climate, hydrological, and water resource modelling tools such as Bharat CLIMEX, UYR-SWAT, and UYRB-WEAP were developed to engage with stakeholders and to analyze climate and hydrological risks, stress-test water policies, and develop adaptation pathways. Over five years (2019-2024), stakeholder engagement (100+ participants) through workshops, interviews, and webinars identified NCT Delhi's water supply reliability, basin-scale demand management, and environmental flow management as key priorities. In the short term, 54.1% of stakeholders supported capacity expansion, while 51.4% prioritized technological adaptation¹. Long-term resilience strategies emphasized continued technological investment (37.8%) and equitable resource allocation (18.9%). Demand reduction measures included targeted subsidies (64.9%), leakage reduction (59.5%), and customer metering (54.1%), with additional support for water pricing (35.1%) and incentives for water-saving technologies (29.7%). While these priorities provide a strong foundation, deep uncertainties in climate change and extreme events threaten their effectiveness. Given the potential for high-impact, low-likelihood (HILL) climate shifts

¹ Stakeholders could select more than one strategy; percentages represent response frequency and may sum to over 100%.

disrupting water availability, stakeholders emphasized the need for climate scenarios encompassing a broad range of plausible futures.

To address HILL climate risks, the study employs the Physical Climate Storylines (PCS) methodology to bridge climate science and hydrological modelling. Climate impact analysis was conducted using CMIP6 datasets, with a particular focus on winter precipitation, which affects water allocation for nine out of twelve months in the Yamuna Basin. The PCS approach was used to explore climate risks, revealing a 30–100% decline in non-monsoon precipitation, a 10–20% increase in monsoon precipitation, and a 2–4°C temperature rise. To capture climate uncertainties, five qualitative climate storylines were developed: S1 (very large decrease), S2 (large decrease), S3 (moderate decrease), S4 (decrease), and S5 (moderate increase) in non-monsoon precipitation. These were translated into quantitative climate data to assess hydrological risks.

A stakeholder-informed fit-for-purpose water resource model was developed using WEAP to translate climate information into hydrological risks. The renewal of the Upper Yamuna Basin Agreement necessitates an operational model tailored to local decision contexts. Model development was guided by stakeholder input and field visits, ensuring that local priorities, allocation rules, and operational constraints were accurately represented. Calibration and validation using Hathnikund Barrage data confirmed the model's reliability, with high NSE and low PBIAS values demonstrating its accuracy. Seasonal variability emerged as a critical challenge, with excessive monsoon flows and severe dry-season shortages exacerbating water stress. Basin-scale water supply and demand simulations revealed Haryana as the largest water consumer, followed by Uttar Pradesh, Delhi, and Rajasthan. The model provided insights into water allocation, demand management, and trade-offs between supply reliability, environmental flow requirements, and socio-economic needs. The model's fit-for-purpose applicability was assessed using closed basin-level water policy questions to ensure it met the needs of stakeholders and technical experts. The model was then used to stress-test adaptation options and develop dynamic adaptation policy pathways (DAPP) using the DMDU approach.

The DMDU modelling framework for UYRB was conceptualized by integrating the XLRM framework and a scenario tree to (1) stress-test water policies and identify tipping points and (2) develop stakeholder-driven DAPP to guide long-term adaptive strategies. The evaluation incorporated demand management strategies identified through stakeholder engagement to enhance NCT Delhi's water supply reliability while ensuring environmental

flow management. Stress-testing results revealed critical tipping points where existing policies and adaptation strategies became ineffective under extreme climate and socio-economic scenarios, such as a very large decrease in non-monsoon precipitation and increased water demand. Under these conditions, severe water shortages emerged, particularly when Yamuna river inflow at the Wazirabad Barrage dropped below historical averages. Demand-side interventions increased Delhi's water supply reliability by 10-30%, while supply-side measures contributed an additional 20-30% to supply reliability and environmental flow management, respectively, improving resilience against extreme climate scenarios. The DAPP approach highlights that early implementation of demand management and wastewater reuse can delay tipping points by 10-20 years, allowing phased infrastructure investments such as reservoir expansion and inter-basin transfers. These findings underscore the necessity of flexible, adaptive water management strategies integrating both supply- and demand-side measures to ensure long-term water security across urban, agricultural, and environmental sectors in the UYRB. The stakeholder-driven approach, incorporating inputs from key agencies such as the Delhi Jal Board and Upper Yamuna River Board, ensures that adaptation pathways are context-specific and responsive to evolving socio-hydrological conditions.

By integrating the co-production approach (Chapter 2), PCS-based climate scenarios (Chapter 3), fit-for-purpose water resource modelling (Chapter 4), stress-testing of water policy options, and stakeholder-driven Dynamic Adaptation Policy Pathways (Chapter 5), this study establishes a decision-centric framework for adaptive water governance. The research highlights the importance of DMDU in tackling water security challenges in the UYRB and NCT Delhi, ensuring stakeholder engagement, leveraging physical climate storyline-based climate scenario analysis, developing fit-for-purpose modelling, and applying stress-testing techniques to evaluate policy tipping points under extreme climate and socio-economic conditions. These insights shape DAPPs, ensuring that adaptive strategies remain flexible, robust, and responsive to evolving uncertainties. This integrated decision-centric framework offers actionable solutions for climate-resilient robust water resource management in data-scarce, climate-vulnerable regions of the Global South.

सारांश

उपरी यमुना नदी बेसिन (UYRB) में जल संसाधन प्रबंधन को जलवायु परिवर्तन, सामाजिक-आर्थिक दबावों और शासन की सीमाओं के कारण बढ़ती चुनौतियों का सामना करना पड़ रहा है। पारंपरिक पूर्वानुमान मॉडल, जो निर्धारक या संभाव्य पूर्वानुमानों पर आधारित होते हैं, गहन अनिश्चितताओं की स्थितियों में जटिलताओं से निपटने में अक्सर असफल रहते हैं। जलवायु परिवर्तन के बढ़ते प्रभाव और बढ़ती मांग को देखते हुए, इस क्षेत्र में लचीला और अनुकूली जल शासन सुनिश्चित करने के लिए ऐसे निर्णय-केंद्रित दृष्टिकोण आवश्यक हैं जो अनेक संभावित भविष्य परिदृश्यों को समाहित कर सकें। यह अध्ययन Decision-Making Under Deep Uncertainty (DMDU) पद्धति को अपनाकर मज़बूत अनुकूलन मार्गों का विकास करता है, जिसमें हितधारकों द्वारा संचालित ज्ञान सह-उत्पादन, भौतिक जलवायु स्टोरीलाइन दृष्टिकोण, उद्देश्यानु रूप मॉडलिंग, अनुकूलन विकल्पों की तनाव-परीक्षण प्रक्रिया, और गतिशील अनुकूलन नीति मार्गों का विकास शामिल है।

एक सह-उत्पादन ढांचा विकसित किया गया, जिसमें सहभागितात्मक मॉडलिंग और निर्णय-सहायता उपकरणों को शामिल किया गया ताकि अनुकूली जल प्रबंधन रणनीतियों का निर्माण किया जा सके। एक बहु-विषयक दृष्टिकोण ने नीति निर्माताओं, शोधकर्ताओं और समुदायों के बीच सहयोग को सक्षम किया, जिससे व्यावहारिक और संदर्भ-विशिष्ट समाधान सुनिश्चित हो सके। विश्लेषण को संरचित करने के लिए XLRM ढांचे का उपयोग किया गया, जिसमें अनिश्चितताओं (X), नीति लीवर (L), परस्पर संबंधों (R), और प्रदर्शन मापदंडों (M) को वर्गीकृत किया गया। भारत CLIMEX, UYR-SWAT, और UYRB-WEAP जैसे जलवायु, जल विज्ञान, और जल संसाधन मॉडलिंग उपकरण विकसित किए गए ताकि हितधारकों की भागीदारी हो सके, जलवायु और जल संबंधी जोखिमों का विश्लेषण किया जा सके, जल नीतियों का तनाव-परीक्षण हो सके और अनुकूलन मार्गों का विकास किया जा सके।

पाँच वर्षों (2019–2024) के दौरान आयोजित कार्यशालाओं, साक्षात्कारों और वेबिनारों के माध्यम से 100 से अधिक प्रतिभागियों की भागीदारी ने एनसीटी दिल्ली की जल आपूर्ति की विश्वसनीयता, बेसिन-स्तरीय मांग प्रबंधन और पर्यावरणीय प्रवाह प्रबंधन को प्रमुख प्राथमिकताओं के रूप में चिन्हित किया। अल्पकालिक रूप में, 54.1% हितधारकों ने क्षमता विस्तार का समर्थन किया, जबकि 51.4% ने प्रौद्योगिकीय अनुकूलन को प्राथमिकता दी। दीर्घकालिक लचीलापन रणनीतियों में सतत प्रौद्योगिकीय निवेश (37.8%) और संसाधनों का न्यायसंगत वितरण (18.9%) पर ज़ोर दिया गया। मांग में कमी लाने के उपायों में लक्षित सब्सिडी (64.9%), लीकेज में कमी (59.5%) और उपभोक्ता मीटरिंग (54.1%) शामिल

थे, जबकि जल मूल्य निर्धारण (35.1%) और जल-बचत प्रौद्योगिकियों के लिए प्रोत्साहन (29.7%) को भी समर्थन प्राप्त हुआ।

यद्यपि ये प्राथमिकताएं एक मज़बूत आधार प्रदान करती हैं, लेकिन जलवायु परिवर्तन और अत्यधिक घटनाओं में गहरी अनिश्चितताएं इनकी प्रभावशीलता को खतरे में डाल सकती हैं। उच्च प्रभाव लेकिन कम संभावना (HILL) वाले जलवायु परिवर्तनों के कारण जल उपलब्धता में रुकावट आने की आशंका को देखते हुए, हितधारकों ने व्यापक संभावित भविष्य परिदृश्यों को समाहित करने वाले जलवायु परिदृश्यों की आवश्यकता पर ज़ोर दिया। इन HILL जलवायु जोखिमों का समाधान करने के लिए, इस अध्ययन में भौतिक जलवायु स्टोरीलाइन (PCS) पद्धति को अपनाया गया ताकि जलवायु विज्ञान और जल संसाधन मॉडलिंग के बीच सेतु बनाया जा सके। CMIP6 डेटासेट का उपयोग करते हुए जलवायु प्रभाव विश्लेषण किया गया, विशेष रूप से सर्दियों की वर्षा पर ध्यान केंद्रित किया गया, जो यमुना बेसिन में नौ में से बारह महीनों तक जल आवंटन को प्रभावित करती है। PCS दृष्टिकोण से यह सामने आया कि गैर-मानसून वर्षा में 30–100% की गिरावट, मानसून वर्षा में 10–20% की वृद्धि, और तापमान में 2–4°C की वृद्धि हो सकती है। जलवायु अनिश्चितताओं को समाहित करने के लिए पांच गुणात्मक जलवायु स्टोरीलाइन विकसित की गईं: S1 (अत्यधिक गिरावट), S2 (बड़ी गिरावट), S3 (मध्यम गिरावट), S4 (सामान्य गिरावट), और S5 (मध्यम वृद्धि)। इनको मात्रात्मक जलवायु आंकड़ों में परिवर्तित कर हाइड्रोलॉजिकल जोखिमों का मूल्यांकन किया गया।

हितधारकों द्वारा सूचित उद्देश्यानुसूचक जल संसाधन मॉडल को WEAP प्लेटफ़ॉर्म पर विकसित किया गया, ताकि जलवायु जानकारी को जल विज्ञान जोखिमों में परिवर्तित किया जा सके। उपरी यमुना बेसिन समझौते के नवीनीकरण की आवश्यकता ने एक ऐसा प्रचालनात्मक मॉडल अनिवार्य कर दिया जो स्थानीय निर्णय संदर्भों के अनुरूप हो। मॉडल विकास हितधारकों की प्रतिक्रिया और क्षेत्रीय भ्रमण से निर्देशित था, जिससे स्थानीय प्राथमिकताओं, आवंटन नियमों और प्रचालन बाधाओं का सटीक प्रतिनिधित्व सुनिश्चित हो सका। हठनीकुंड बैराज के डेटा के उपयोग से मॉडल का अंशांकन और सत्यापन किया गया, जिसमें उच्च NSE और न्यून PBIAS मानों ने इसकी सटीकता को प्रमाणित किया। मौसमी परिवर्तनशीलता एक प्रमुख चुनौती के रूप में सामने आई, जिसमें अत्यधिक मानसूनी प्रवाह और सूखे मौसम की गंभीर कमी ने जल संकट को और बढ़ा दिया। बेसिन स्तर पर जल आपूर्ति और मांग के सिमुलेशन में हरियाणा को सबसे बड़ा जल उपयोगकर्ता पाया गया, इसके बाद उत्तर प्रदेश, दिल्ली और राजस्थान रहे। मॉडल ने जल आवंटन, मांग प्रबंधन, और आपूर्ति विश्वसनीयता, पर्यावरणीय प्रवाह आवश्यकताओं, और सामाजिक-आर्थिक ज़रूरतों के बीच संतुलन के निर्णयों में अंतर्दृष्टि प्रदान की।

मॉडल की उद्देश्यानु रूप उपयोगिता को बंद-बेसिन जल नीति प्रश्नों के ज़रिए परखा गया ताकि यह सुनिश्चित किया जा सके कि यह हितधारकों और तकनीकी विशेषज्ञों की आवश्यकताओं को पूरा करता है। इसके बाद DMDU पद्धति के अंतर्गत अनुकूलन विकल्पों का तनाव-परीक्षण किया गया और गतिशील अनुकूलन नीति मार्ग (DAPP) विकसित किए गए।

UYRB के लिए DMDU मॉडलिंग ढांचे की परिकल्पना XLRM ढांचे और परिदृश्य वृक्ष के एकीकरण द्वारा की गई, ताकि (1) जल नीतियों का तनाव-परीक्षण किया जा सके और निर्णायक बिंदुओं (tipping points) की पहचान हो सके और (2) हितधारकों द्वारा संचालित DAPP को विकसित कर दीर्घकालिक अनुकूलन रणनीतियों का मार्गदर्शन मिल सके। मूल्यांकन प्रक्रिया में उन मांग प्रबंधन रणनीतियों को शामिल किया गया जिन्हें हितधारक परामर्श के दौरान पहचाना गया था, जिससे एनसीटी दिल्ली की जल आपूर्ति विश्वसनीयता में सुधार लाया जा सके और साथ ही पर्यावरणीय प्रवाह प्रबंधन सुनिश्चित किया जा सके। तनाव-परीक्षण के परिणामों ने यह स्पष्ट किया कि कुछ गंभीर जलवायु और सामाजिक-आर्थिक परिदृश्यों — जैसे गैर-मानसून वर्षा में अत्यधिक गिरावट और बढ़ी हुई जल मांग — की स्थितियों में वर्तमान नीतियाँ और रणनीतियाँ अप्रभावी हो जाती हैं। ऐसे परिदृश्यों में, विशेष रूप से जब वज़ीराबाद बैराज पर यमुना नदी का प्रवाह ऐतिहासिक औसत से कम हो गया, तो गंभीर जल संकट उत्पन्न हुआ। मांग-पक्ष हस्तक्षेपों से दिल्ली की जल आपूर्ति विश्वसनीयता में 10–30% तक सुधार हुआ, जबकि आपूर्ति-पक्ष उपायों से 20–30% तक अतिरिक्त सुधार हुआ, जिससे अत्यधिक जलवायु परिस्थितियों के प्रति लचीलापन बढ़ा। DAPP पद्धति यह दर्शाती है कि यदि मांग प्रबंधन और अपशिष्ट जल पुनः उपयोग को समय पर लागू किया जाए तो tipping points को 10–20 वर्षों तक टाला जा सकता है, जिससे जलाशयों का विस्तार और अंतर्बेसिन स्थानांतरण जैसे चरणबद्ध बुनियादी ढांचा निवेश संभव हो पाते हैं।

ये निष्कर्ष इस बात को रेखांकित करते हैं कि UYRB क्षेत्र में शहरी, कृषि और पर्यावरणीय क्षेत्रों में दीर्घकालिक जल सुरक्षा सुनिश्चित करने के लिए लचीली और अनुकूली जल प्रबंधन रणनीतियाँ अनिवार्य हैं, जो आपूर्ति और मांग दोनों पक्षों के उपायों को एकीकृत करती हों। हितधारकों द्वारा संचालित यह दृष्टिकोण, जिसमें दिल्ली जल बोर्ड और उपरी यमुना नदी बोर्ड जैसी प्रमुख एजेंसियों के इनपुट शामिल हैं, यह सुनिश्चित करता है कि अनुकूलन मार्ग विशिष्ट संदर्भों के अनुसार हों और बदलते सामाजिक-जलविज्ञानी परिदृश्यों के प्रति उत्तरदायी हों।

सह-उत्पादन दृष्टिकोण (अध्याय 2), PCS-आधारित जलवायु परिदृश्य (अध्याय 3), उद्देश्यानुसूचित जल संसाधन मॉडलिंग (अध्याय 4), जल नीति विकल्पों का तनाव-परीक्षण, और हितधारकों द्वारा संचालित गतिशील अनुकूलन नीति मार्ग (अध्याय 5) को एकीकृत करके यह अध्ययन एक निर्णय-केंद्रित अनुकूलन ढांचा प्रस्तुत करता है जो अनुकूली जल शासन को समर्थन देता है। यह शोध दर्शाता है कि DMDU दृष्टिकोण UYRB और NCT दिल्ली में जल सुरक्षा संबंधी चुनौतियों से निपटने में किस प्रकार सहायक हो सकता है, जिसमें हितधारकों की भागीदारी, भौतिक जलवायु स्टोरीलाइन-आधारित जलवायु विश्लेषण, उद्देश्यानुसूचित मॉडलिंग का विकास, और चरम जलवायु तथा सामाजिक-आर्थिक परिस्थितियों में नीति tipping points के मूल्यांकन हेतु तनाव-परीक्षण तकनीकों का प्रयोग शामिल है। ये अंतर्दृष्टियाँ DAPPs को आकार देती हैं, जिससे अनुकूलन रणनीतियाँ लचीली, मज़बूत और अनिश्चितताओं के प्रति उत्तरदायी बनी रहती हैं। यह एकीकृत निर्णय-केंद्रित ढांचा डेटा-कमी और जलवायु-संवेदनशील वैश्विक दक्षिण के क्षेत्रों में जलवायु-सहिष्णु मज़बूत जल संसाधन प्रबंधन के लिए व्यावहारिक समाधान प्रस्तुत करता है।

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ABBREVIATIONS

AO	Adaptation Options
APHRODITE	Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation
CLIMEX	Climate Extremes for India Region
CMIP6	Coupled Model Intercomparison Project Phase 6
CMIP6-MME - CMIP6	Multi Model Ensemble
CORDEX	Coordinated Regional Climate Downscaling Experiment
CWC	Central Water Commission
DAPP	Dynamic Adaptation Policy Pathways
DJB	Delhi Jal Board
DMDU	Decision Making under Deep Uncertainty
DWP	Delhi Water policy
ENSO	El Niño–Southern Oscillation
GCRF	Global Challenge Research Fund
HILL	High Impact Low likelihood
IMD	Indian Metrological Department
IMERG	Integrated Multi-satellitE Retrievals for GPM (Global Precipitation Measurement)
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCR	National Capital Region
NCT	National Capital Territory
NEX-GDDP	NASA Earth Exchange - Global Daily Downscaled Projections
NGT	National Green Tribunal
NIH	National Institute of Hydrology
NOAA	National Oceanic and Atmospheric Administration
NRW	Non-Revenue Water
PCS	Physical Climate Storylines
PEST	Parameter ESTimation (a model-independent parameter estimation tool)
RDM	Robust Decision Making
SWC	Soil Water Conservation

TRMM	Tropical Rainfall Measuring Mission
UKRI	United Kingdom Research and Innovation
UYRB	Upper Yamuna River Basin
UYRB-WEAP	Upper Yamuna River Basin Water Evaluation And Planning
WEAP	Water Evaluation And Planning
WJC	Western Jamuna Canal
XLRM	Uncertainties(X), Lever (L), Relationships (R), Metrics (M)
YMC	Yamuna Monitoring Committee