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THE UNIVERSITY OF QUEENSLAND
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DEVELOPING AN UNDERSTANDING OF MACROINVERTEBRATE ASSEMBLAGE'S RESPONSE TO THE COMBINED EFFECT OF CHANGES IN FLOW REGIMES, WATER QUALITY AND CLIMATE CHANGE IN THE GOULBURN RIVER IN AUSTRALIA

SUDEEP BANAD

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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THE UNIVERSITY OF QUEENSLAND

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Developing an understanding of macroinvertebrate assemblage's response to the combined effect of changes in flow regimes, water quality and climate change in the Goulburn River in Australia

by

SUDEEP BANAD

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in fulfilment of the requirements for the joint degree of

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&

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Dedicated to

Kasturi Banad (mother), Vivekanand Banad (father) and Rituparna Das (wife)

Three strong and gentle souls who always inspire me to live up to my full potential.

Supervisor Certification

This is to certify that the thesis entitled "**Developing an understanding of macroinvertebrate assemblage's response to the combined effect of changes in flow regimes, water quality and climate change in the Goulburn River in Australia**" being submitted by **Mr. Sudeep Banad** to the Indian Institute of Technology Delhi and The University of Queensland for the award of degree of **Doctor of Philosophy** is a record of *bonafide* research work carried out by him. **Mr. Sudeep Banad** has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The results contained in this thesis are original and have not been submitted, in part or full, to any other University or Institute for the award of any other degree or diploma.

Prof. Dhanya C T

Department of Civil Engineering

Indian Institute of Technology Delhi, India 110016

Prof. Yongping Wei

School of the Environment

University of Queensland

St. Lucia, Australia - 4076

Prof. Ron Johnstone

School of the Environment

University of Queensland

St. Lucia, Australia - 4076

Abstract

Freshwater ecosystems are vital, supporting a significant portion of global biodiversity, but they are increasingly stressed by regulatory structures such as dams and water diversion schemes, as well as the impacts of climate change. These regulatory structures directly influence the five key components of the natural flow regime—magnitude, frequency, duration, timing, and rate of change—disrupting the ecological balance within these ecosystems. There is a lack of studies that examine the combined impact of flow alterations, water quality changes, and climate change on freshwater ecosystems, particularly at a local level, thus compromising the environmental flow design and implementation.

This PhD study aims to develop a comprehensive understanding of how macroinvertebrate assemblages, key species within the aquatic food web, have responded to changes in flow regimes and water quality resulting from river regulation and extreme drought events, focusing on both regulated and unregulated reaches of the Goulburn River in Australia. Specifically, this PhD study has the following three research questions (objectives): 1) How did macroinvertebrate assemblages respond to ecologically relevant streamflow characteristics? 2) How did macroinvertebrate assemblages respond to changes in ecologically relevant streamflow indices and water quality stressors during a severe drought? 3) How will climate change impact ecologically relevant streamflow indices and their implications for aquatic ecosystems, including macroinvertebrate assemblages?

Firstly, this study quantified the relationship between macroinvertebrate biotic indices and key streamflow characteristics derived from five components of the natural flow regime. Using boosted regression trees (BRT), the results revealed significant hydrological variability between reaches: regulated reaches exhibited reduced variability during low flow periods and rapid discharge increases during high flow periods, while the unregulated reach had 38% higher taxa richness. Eight indicator taxa were identified in the unregulated reach, which also displayed higher Stream Invertebrate Grade Number Average Level (SIGNAL 2) scores, indicating sensitivity to flow changes. The maximum flow in June was identified as the most influential flow parameter affecting macroinvertebrate indices.

Secondly, this study examined the combined effects of streamflow variation and water quality during the Millennium Drought, one of Australia's most severe climatic events. Using redundancy analysis (RDA) and threshold indicator taxa analysis (TITAN), this study showed significant spatial and temporal variations in taxa richness, abundance, diversity, and EPT indices between drought and post-drought periods. Post-drought, all reaches demonstrated increased richness and abundance, with Shannon and

EPT indices notably improving. Analysis of Similarities (ANOSIM) revealed greater taxonomic dissimilarity across reaches post-drought.

Thirdly, this study assessed the potential impacts of climate change on ecologically relevant streamflow indices. Using the Soil and Water Assessment Tool (SWAT) model, this study projected daily streamflow based on downscaled, bias-corrected temperature and precipitation data from six CMIP5 General Circulation Models (GCMs) under two Representative Concentration Pathways (RCP 4.5 and RCP 8.5). Results revealed a significant increase in hydrological variability, with minimum flows dropping to zero during November and high pulse counts (flow events exceeding the 75th percentile) tripling under both RCP scenarios, which are expected to have profound consequences for freshwater ecosystems, particularly benthic macroinvertebrates.

This study has great implications for future environmental flow management by extending our understanding of how variations in the five components of natural flow regimes—magnitude, frequency, duration, timing, and rate of change—impact ecosystem health, deepening the existing understanding of macroinvertebrate resilience to flow variability and water quality changes, and by offering new insights into how climate-induced hydrological shifts affect freshwater ecosystems from a perspective of integrated hydrology and ecology. It will assist in more flexible, and more systemic environmental flow management suitable for local conditions and adapt to climate changes.

Abstract in Hindi

मीठे पानी के पारिस्थितिक तंत्र महत्वपूर्ण हैं, जो वैश्विक जैव विविधता का एक महत्वपूर्ण हिस्सा समर्थन करते हैं, लेकिन वे बांधों और जल परिवर्तनों जैसी नियामक संरचनाओं, साथ ही जलवायु परिवर्तन के प्रभावों से लगातार दबाव में हैं। ये नियामक संरचनाएं प्राकृतिक प्रवाह शासन के पांच मुख्य घटकों—परिमाण, आवृत्ति, अवधि, समय, और परिवर्तन की दर—को सीधे प्रभावित करती हैं, जिससे इन पारिस्थितिक तंत्रों में संतुलन बिगड़ता है। प्रवाह में परिवर्तनों, जल गुणवत्ता में बदलाव और जलवायु परिवर्तन के संयुक्त प्रभावों का अध्ययन करने में कमी है, विशेष रूप से स्थानीय स्तर पर, जिससे पर्यावरणीय प्रवाह के डिजाइन और कार्यान्वयन पर प्रतिकूल प्रभाव पड़ता है।

यह पीएचडी अध्ययन इस बात की समग्र समझ विकसित करने का प्रयास करता है कि जलीय खाद्य श्रृंखला की मुख्य प्रजातियाँ, मैक्रोइनवर्टेब्रेट असेंबलियां, नदी नियमन और अत्यधिक सूखा घटनाओं के परिणामस्वरूप प्रवाह शासन और जल गुणवत्ता में परिवर्तनों पर कैसे प्रतिक्रिया करती हैं। अध्ययन में ऑस्ट्रेलिया की गॉलबर्न नदी के दोनों विनियमित और अविनियमित हिस्सों पर ध्यान केंद्रित किया गया है, जो मीठे पानी के पारिस्थितिक तंत्रों में परिवर्तित प्राकृतिक प्रवाह शासन, जल गुणवत्ता और जलवायु परिवर्तन के बीच जटिल संबंधों का उदाहरण प्रस्तुत करती है। विशेष रूप से, इस पीएचडी अध्ययन के तीन शोध प्रश्न (उद्देश्य) हैं: 1) मैक्रोइनवर्टेब्रेट असेंबलियों ने पारिस्थितिक रूप से प्रासंगिक प्रवाह विशेषताओं पर कैसे प्रतिक्रिया दी? 2) अत्यधिक सूखे के दौरान पारिस्थितिक रूप से प्रासंगिक प्रवाह सूचकांकों और जल गुणवत्ता के तनावों में परिवर्तनों पर मैक्रोइनवर्टेब्रेट असेंबलियों ने कैसे प्रतिक्रिया दी? 3) जलवायु परिवर्तन पारिस्थितिक रूप से प्रासंगिक प्रवाह सूचकांकों और जलीय पारिस्थितिक तंत्रों, जिनमें मैक्रोइनवर्टेब्रेट असेंबलियां शामिल हैं, पर क्या प्रभाव डालेगा?

पहले, इस अध्ययन ने प्राकृतिक प्रवाह शासन के पांच घटकों से व्युत्पन्न मुख्य प्रवाह विशेषताओं और मैक्रोइनवर्टेब्रेट जैविक सूचकांकों के बीच संबंध को मापा। बूस्टेड रिग्रेशन ट्रीज़ (BRT) का उपयोग करके परिणामों ने यह दिखाया कि विनियमित हिस्सों में निम्न प्रवाह अवधियों के दौरान प्रवाह में कम विविधता और उच्च प्रवाह अवधियों के दौरान तीव्र प्रवाह वृद्धि देखी गई, जबकि अविनियमित हिस्से में टैक्सा विविधता 38% अधिक थी। अविनियमित हिस्से में आठ सूचक टैक्सा पहचाने गए, जो प्रवाह परिवर्तनों के प्रति संवेदनशीलता दर्शाते हुए उच्च स्ट्रीम इनवर्टेब्रेट ग्रेड नंबर एवरेज लेवल (SIGNAL 2) स्कोर प्रदर्शित करते हैं। जून में अधिकतम प्रवाह को मैक्रोइनवर्टेब्रेट सूचकांकों को प्रभावित करने वाला सबसे महत्वपूर्ण प्रवाह पैरामीटर पाया गया।

दूसरे, इस अध्ययन ने ऑस्ट्रेलिया की सबसे गंभीर जलवायु घटनाओं में से एक, मिलेनियम ड्रॉट के दौरान प्रवाह भिन्नता और जल गुणवत्ता के संयुक्त प्रभावों की जांच की। रिडंडेंसी एनालिसिस (RDA) और थ्रेशोल्ड इंडिकेटर टैक्सा एनालिसिस (TITAN) का उपयोग करते हुए, इस अध्ययन ने टैक्सा विविधता, प्रचुरता, विविधता, और EPT सूचकांकों में सूखे और सूखे के बाद की अवधियों के बीच महत्वपूर्ण स्थानिक और कालिक भिन्नताएँ दिखाई। सूखे के बाद, सभी हिस्सों में विविधता और प्रचुरता में वृद्धि हुई, और शैनन और EPT सूचकांक में उल्लेखनीय सुधार देखा गया। ANOSIM ने सूखे के बाद हिस्सों में टैक्सोनोमिक विषमता में वृद्धि दिखाई।

तीसरे, इस अध्ययन ने पारिस्थितिक रूप से प्रासंगिक प्रवाह सूचकांकों पर जलवायु परिवर्तन के संभावित प्रभावों का आकलन किया। SWAT मॉडल का उपयोग करते हुए, इस अध्ययन ने दैनिक प्रवाह को छह CMIP5 जनरल सर्कुलेशन मॉडल (GCMs) से डाउनस्केल, बायस-संशोधित तापमान और वर्षा डेटा के आधार पर दो प्रतिनिधि सांद्रता पथों (RCP 4.5 और RCP 8.5) के तहत प्रक्षेपित किया। परिणामों ने हाइड्रोलॉजिकल विविधता में महत्वपूर्ण वृद्धि का खुलासा किया, जिसमें न्यूनतम प्रवाह नवंबर के दौरान शून्य हो गया और उच्च पल्स गणना (75वें पर्सेंटाइल से अधिक प्रवाह घटनाएं) दोनों RCP परिदृश्यों के तहत तिगुनी हो गईं, जो विशेष रूप से बेंटिक मैक्रोइनवर्टेब्रेट्स के लिए मीठे पानी के पारिस्थितिक तंत्रों पर गहरे परिणाम डालने की संभावना है।

इस अध्ययन के भविष्य में पर्यावरणीय प्रवाह प्रबंधन के लिए महत्वपूर्ण प्रभाव हैं, क्योंकि यह इस बात की हमारी समझ को बढ़ाता है कि प्राकृतिक प्रवाह शासन के पांच घटकों—परिमाण, आवृत्ति, अवधि, समय और परिवर्तन की दर—में भिन्नताएँ पारिस्थितिकी तंत्र के स्वास्थ्य को कैसे प्रभावित करती हैं। यह प्रवाह भिन्नता और जल गुणवत्ता परिवर्तनों के प्रति मैक्रोइनवर्टेब्रेट्स की सहनशीलता की मौजूदा समझ को गहरा करता है, और यह नए सैद्धांतिक अंतर्दृष्टि प्रदान करता है कि जलवायु-प्रेरित हाइड्रोलॉजिकल परिवर्तनों से मीठे पानी के पारिस्थितिक तंत्र कैसे प्रभावित होते हैं। यह स्थानीय परिस्थितियों के लिए अधिक सूक्ष्म, अधिक लचीला, और अधिक प्रणालीगत पर्यावरणीय प्रवाह प्रबंधन को सक्षम बनाने में सहायता करेगा और जलवायु परिवर्तनों के अनुकूल बने रहने में मदद करेगा।

Declaration by author

This thesis is composed of my original work and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution of others to jointly authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, financial support and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my higher degree by research candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

I acknowledge that an electronic copy of my thesis must be lodged with the University Library and, subject to the policy and procedures of The University of Queensland, the thesis be made available for research and study in accordance with the Copyright Act 1968 unless a period of embargo has been approved by the Dean of the Graduate School.

I acknowledge that copyright of all material contained in my thesis resides with the copyright holder(s) of that material. Where appropriate I have obtained copyright permission from the copyright holder to reproduce material in this thesis and have sought permission from co-authors for any jointly authored works included in the thesis.

Publications included in this thesis

This thesis includes one published peer-reviewed journal article, which has been incorporated as the core results chapter. This chapter has been retained in its original article format in publication. Contributions of all authors to the publications are indicated as follows:

1. **Banad, S.,** Wei, Y., Dhanya, C. T., & Johnstone, R. (2023). **Effects of altered streamflow on macroinvertebrate taxonomic richness and composition in the Goulburn River, Australia**. Frontiers in Environmental Science, 11, 1134108**.** Incorporated as Chapter 3.

Author/Contributor	Statement of contribution
Sudeep Banad	Conception and design of the study (75%)
	Data collection and analysis (100%)
	Drafting and editing the paper (75%)
Yongping Wei	Conception and design of the study (10%)
	Drafting and editing the paper (10%)
Dhanya C T	Conception and design of the study (10%)
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Ron Johnstone	Conception and design of the study (5%)
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Conference publications:

- **Banad, S**., Wei, Y., Dhanya, C. T., & Johnstone, R. (2023, May). **Investigating the effects of river regulation and water quality on macroinvertebrate communities in the Goulburn basin during the millennium drought**. In EGU General Assembly Conference Abstracts (pp. EGU-9147).
- **Banad, S**., Wei, Y., & C T, Dhanya. (2020, December). **Implications of river regulation on in-stream ecosystems in Goulburn River, Australia**. In AGU Fall Meeting Abstracts (Vol. 2020, pp. H122-01).

Submitted manuscripts included in this thesis

This thesis includes two manuscripts submitted to peer-reviewed journals. The thesis has incorporated these manuscripts as the core result chapters in their original journal article formats. Contributions of all authors to the manuscripts are indicated as follows:

2. **Banad, S.,** Wei, Y., Dhanya, C. T., & Johnstone, R**. Sensitivity Macroinvertebrate Response to Streamflow and Water Quality Stressors during the Millennium Drought**. *To be submitted to Journal of Environmental management* – Incorporated as Chapter 4.

Author/Contributor	Statement of contribution
Sudeep Banad	Conception and design of the study (75%) Data collection and analysis (100%) Drafting and editing the paper (75%)
Yongping Wei	Conception and design of the study (10%) Drafting and editing the paper (10%)
Dhanya C T	Conception and design of the study (10%) Drafting and editing the paper (10%)
Ron Johnstone	Conception and design of the study (5%) Drafting and editing the paper (5%)

3. **Banad, S.,** Wei, Y., Dhanya, C. T., & Johnstone, R. **Effects of climate change on ecologically sensitive flows in the Goulburn Catchment, Australia**. *To be submitted to Advances in Water Resources*– Incorporated as Chapter 5.

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Sudeep Banad	Conception and design of the study (75%) Data collection and analysis (100%) Drafting and editing the paper (75%)
Yongping Wei	Conception and design of the study (10%) Drafting and editing the paper (10%)
Dhanya C T	Conception and design of the study (10%) Drafting and editing the paper (10%)
Ron Johnstone	Conception and design of the study (5%) Drafting and editing the paper (5%)

Statement of parts of the thesis submitted to qualify for the award of another degree

No works submitted towards another degree have been included in this thesis.

Research involving human or animal subjects

No animal or human subjects were involved in this research.

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Keywords

aquatic ecosystem, macroinvertebrates, taxonomic composition, flow metrics, water quality, millennium drought, river regulation, climate change, environmental flows, SWAT model.

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ANZSRC code: 040608, Surface water Hydrology, 30%

ANZSRC code: 961199, Physical and Chemical Conditions of Water not elsewhere classified, 10%

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FoR code: 0502, Environmental Science and Management, 60%

FoR code: 0406, Physical Geography and Environmental Geoscience, 30%

FoR code: 9611, Physical and Chemical Conditions of Water, 10%

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