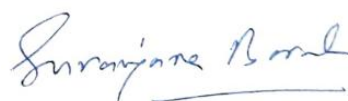


DECLARATION

I hereby declare that the thesis entitled “**Hydrogeomorphic and land cover dynamics of Manas-Beki river basin with special emphasis on the glacial regime**” submitted to the **School of Sciences**, Tezpur University in part fulfillment for the award of the degree of Doctor of Philosophy in **Environmental Science** is a record of research work carried out by me under the supervision of **Prof. Apurba K. Das**, Department of Environmental Science, Tezpur University, Assam - 784028. No part of this work has been presented for any other degree or diploma earlier.

Date: 12-04-2023

Place: Tezpur



(Suranjana Bhaswati Borah)

Department of Environmental Science

School of Sciences

Tezpur University, Assam, India



तेजपुरविश्वविद्यालय/ TEZPUR UNIVERSITY

(संसदकेअधिनियमद्वारास्थापितकेंद्रीयविश्वविद्यालय)

(A Central University established by an Act of Parliament)

तेजपुर-784028 :: असम/ TEZPUR-784028 :: ASSAM

(सर्वोत्तम विश्वविद्यालय के लिए कुलाध्यक्ष पुरस्कार, 2016 और भारत के 100 श्रेष्ठ उच्च शिक्षण संस्थानों में पंचम स्थान प्राप्त विश्वविद्यालय)
(Awardee of Visitor's Best University Award, 2016 and 5th among India's Top 100 Universities, MHRD-NIRF Ranking, 2016)

Certificate of the Supervisor

This is to certify that the thesis entitled “**Hydrogeomorphic and land cover dynamics of Manas-Beki river basin with special emphasis on the glacial regime**” submitted to the **School of Sciences**, Tezpur University, in part fulfillment for the award of the degree of Doctor of Philosophy in **Environmental Science** is a record of research work carried out by **Ms. Suranjana Bhaswati Borah** under my supervision and guidance.

All help received by her from various sources has been duly acknowledged.

No part of this thesis has been submitted elsewhere for award of any other degree.

A handwritten signature in black ink, appearing to read 'Apurba K. Das'.

Date: 12-04-2023

Place: Tezpur University

(Dr. Apurba K. Das)

Designation: Professor

Department: Environmental Science

School: School of Sciences

Acknowledgment

This research work would not have been completed without the help and support of many people who have contributed in some way or the other towards the successful completion of the thesis and it is my pleasure to acknowledge and express my gratitude to each and everyone involved.

In the beginning, I would like to convey my deepest sense of gratitude and sincere thanks to my supervisor Prof. Apurba Kumar Das for his invaluable inspiration, patient guidance, constant encouragement, and constructive criticism throughout the research work. He was more like a close family member beside his role as a guide who helped me overcome all the hurdles that I had to face during my Ph.D. tenure.

I would like to thank Tezpur University for providing me with the opportunity and necessary facilities to pursue my Ph.D. I am grateful to DST-SERB for providing the fellowship during the initial phase of my research work while I was involved with the project titled “Hydrogeomorphic characterization of Manas-Aie and Gaurang river basins–A baseline study of Geomorphic response to observed precipitation change over Indian region” (Grant Number SB/EMEQ-108/2013).

I would like to offer my sincere thanks to my Doctoral Committee members, Retd. Prof. K.P. Sarma, Prof. Sarat Saharia, Prof. R.R. Hoque, and Dr. Sumi Handique for their valuable suggestions and constructive criticism of my work, which helped in shaping the structure of the work in an appropriate way. I also offer my gratitude to the faculty members of the Department of Environmental Science, Tezpur University for their valuable suggestions.

I would like to acknowledge Dr. Anil V. Kulkarni, Divecha Centre for Climate Change, IISc, Bangalore who planted the research idea in my mind and P.L.N. Raju, Ex-Director of North Eastern Space Applications Centre (NESAC), Meghalaya, for sharing new ideas and methods to improve my research.

I would like to especially thank my friends, ex-classmates, and lab mates Dr. Nabajit Hazarika, and Dr. Rajesh Kumar Sah for their endless help and emotional support, and my Tezpur University lab mates Dr. Juri Borbora, Dr. Himolin Basumatary, Ms. Bharati Paul, Ms. Roto Yalyo, Ms. Sabrina Begum, Ms. Debashree Dutta, Ms. Dhriti Kalita, and Mr. Biplab Sarmah for their support throughout my research work. I would also like to extend my sincere thanks to the entire family of the department, who in some way or other, have contributed to this endeavor including all research scholars and office support staff.

Life at Tezpur University was worth living because of a few persons, who have always encouraged and helped me in every possible way, my hostel mates Ruksana, Riju, Hima and Kuntala. I am also thankful to my other friends and work colleagues at USTM, NESAC, and IRRI for always being there and constantly pushing me towards completion. Many other friends and hostel mates remain unnamed because of space constrains and I am grateful for their support in completing my research.

Finally, I am forever indebted to Mom and Dad who believed in me till their last breath and showered me with their unconditional love, motivation, support, encouragement, blessings, and prayer in every step of my life. I am also thankful to my sister and her family for their constant encouragement and support. One person without whom my thesis would not be completed and who has eagerly waited to see me complete my Ph.D. is my better half. I thank him for his constant encouragement, care, physical and moral support to finish my thesis.

(Suranjana Bhaswati Borah)

LIST OF TABLES

Chapter	Table No.	Table caption	Page No.
2	2.1	Details of data used for hydrogeomorphic characterization of Manas-Beki river basin	16
	2.2	Morphometric parameters and their mathematical expressions	17
	2.3	Linear aspect of Manas-Beki river basin	21
	2.4	Areal parameters of Manas-Beki river basin	22
	2.5	Sinuosity values estimated for floodplain reach of Manas-Beki river, 1990-2020	25
	2.6	Total sinuosity values estimated for floodplain reach of Manas-Beki river, 1990-2020	28
	2.7	Channel count index for floodplain reach of Manas-Beki river, 1990-2020	30
	2.8	Thalweg shift between 1990 to 2020 for the Manas-Beki river	33
	2.9	Values of bank line shift between 1990 to 2020 for left and right bank of Manas-Beki river	37
	2.10	Values of channel width at each cross-section from 1990 to 2020 for Manas-Beki river	40
	2.11	Erosion and deposition areas for different reaches of Manas-Beki river during 1990-2020 (Areas in sq km)	44
3	3.1	Details of satellite data used for LULC change analysis in Manas-Beki basin, 1990-2020	59
	3.2	LULC classes adopted for change analysis in Manas-Beki basin	61
	3.3	Criteria used for extraction of snow and ice-covered areas in Manas-Beki basin	65
	3.4a	Confusion matrix for hybrid classification of Manas-Beki floodplain region, 1990	67

	3.4b	Confusion matrix for hybrid classification of Manas-Beki floodplain region, 2000	67
	3.4c	Confusion matrix for hybrid classification of Manas-Beki floodplain region, 2010	68
	3.4d	Confusion matrix for hybrid classification of Manas-Beki floodplain region, 2020	68
	3.5	LULC statistics in the floodplains of Manas-Beki river during 1990, 2000, 2010 and 2020	71
	3.6a	Change matrix of LULC classes in floodplain of Manas-Beki river, 1990-2000	72
	3.6b	Change matrix of LULC classes in floodplain of Manas-Beki river, 2000-2010	72
	3.6c	Change matrix of LULC classes in floodplain of Manas-Beki river, 2010-2020	72
	3.7	LULC classes in Manas-Beki floodplain affected by erosion and deposition during 1990-2020	73
	3.8	Mean NDVI values for different sub-basins in Manas-Beki basin (1990-2020)	74
4	4.1	Details of satellite data used for analysis of glacier and high-altitude lakes in Manas-Beki basin	99
	4.2	Types of changes in glaciers of Manas-Beki river basin and the affected areas during 1990–2020	108
	4.3	Types of changes in high-altitude lakes of Manas-Beki river basin and the affected areas during 1990–2020	116

LIST OF FIGURES

Chapter	Figure No.	Figure caption	Page No.
1	1.1	Location of the Study Area	6
2	2.1	The schema of methodology used for hydrogeomorphic characterization of Manas-Beki river basin	17
	2.2	Cross-sections and reaches identified for change analysis, Manas-Beki river	19
	2.3	Basin boundary and delineated streams of Manas-Beki river basin	20
	2.4	Hypsometry of Manas-Beki river system	20
	2.5	Distribution of different slope classes in Manas-Beki river basin	23
	2.6(a)	Landsat satellite images showing the foothills region of the Manas-Beki river	24
	2.6(b)	Landsat satellite images showing the confluence region of the Manas-Beki river	24
	2.7	Sinuosity values from 1990 to 2020 for the floodplain reach of Manas-Beki river	26
	2.8(a)	Sinuosity values from 1990 to 2020 for the Manas main channel	26
	2.8(b)	Sinuosity values from 1990 to 2020 for the Beki sub-section	27
	2.9	Total sinuosity values from 1990 to 2020 for the floodplain reach of Manas-Beki river	27
	2.10(a)	Total sinuosity values from 1990 to 2020 for the Manas main channel	29
	2.10(b)	Total sinuosity values from 1990 to 2020 for the Beki sub-section	29
	2.11	Changes in values of channel count index in Manas-Beki basin from 1990 to 2020	30

2.12(a)	Channel count index values from 1990 to 2020 for the Manas main channel	31
2.12(b)	Channel count index values from 1990 to 2020 for the Beki sub-section	32
2.13	River thalwegs from 1990 to 2020 for the (a) upstream reach of NH crossing, and (b) downstream of NH crossing	33
2.14(a)	Thalweg shifts at each cross-section of main channel Manas	34
2.14(b)	Thalweg shifts at each cross-section of the Beki sub-section	35
2.15	River banklines from 1990 to 2020 for the (a) upstream reach of NH crossing, and (b) downstream of NH crossing	36
2.16(a)	Bank line shifts in the left bank at each cross-section of main channel Manas	38
2.16(b)	Bank line shifts in the left bank at each cross-section of Beki sub-section	38
2.17(a)	Bank line shifts in the right bank at each cross-section of main channel Manas	39
2.17(b)	Bank line shifts in the right bank at each cross-section of Beki sub-section	39
2.18(a)	Changes in channel width at each cross-section of main channel Manas	41
2.18(b)	Changes in channel width at each cross-section of Beki sub-section	41
2.19	Erosion and deposition areas due to changes in river channel course in Manas-Beki river during (a) 1990-2000 (b) 2000-2010, and (c) 2010-2020	42
2.20	Erosion and deposition areas in Manas-Beki river during 1990-2020	43
2.21(a)	Erosion and deposition areas for each reach of Manas main channel	43

	2.21(b)	Erosion and deposition areas for each reach of Beki sub-section	43
	2.22(a)	Net area change due to erosion and deposition for each reach of Manas main channel	45
	2.22(b)	Net area change due to erosion and deposition for each reach of Beki sub-section	45
3	3.1	Flowchart of overall methodology used for land use and land cover classification and change analysis	59
	3.2	LULC classes in the Manas-Beki river basin	60
	3.3	Glaciated upper catchments with their areas for vegetation and snow cover analysis from 1990 to 2020	64
	3.4	LULC in the Manas-Beki floodplain region for (a) 1990, (b) 2000, (c) 2010 and (d) 2020	69
	3.5	Percentage areas under different LULC categories for 1990, 2000, 2010 and 2020 in Manas-Beki floodplains	70
	3.6	Area change in LULC categories in Manas-Beki floodplains, 1990-2020	70
	3.7	Area change in LULC categories due to erosion and deposition in Manas-Beki floodplains, 1990-2020	73
	3.8	Mean NDVI values for each sub-basin in Manas-Beki basin (1990-2020)	74
	3.9	NDVI difference image (1990-2020) showing change and no change areas in upper catchments of Manas-Beki basin	75
	3.10	Vegetation cover area based on NDVI for Manas-Beki upper catchments (1990, 2000, 2010 and 2020)	76
	3.11	Vegetation area changes in percentage from 1990-2020 in Manas-Beki upper catchments	76
	3.12	Snow cover area based on NDSI for Manas-Beki upper catchments (1990, 2000, 2010 and 2020)	77
	3.13	Snow cover area changes in percentage from 1990-2020 in Manas-Beki upper catchments	78

	3.14	Seasonal snow cover area in (a)1990 and (b) 2020) for the Manas-Beki basin	79
	3.15	Seasonal snow cover area changes in percentage (1990 - 2020) for the Manas-Beki basin	80
	3.16(a)	Average snow cover (in %) in Mangde Chu Basin for December (1990-2020)	81
	3.16(b)	Average snow cover (in %) in Chamkar Chu Basin for December (1990-2020)	81
	3.16(c)	Average snow cover (in %) in Kuri Chu Basin for December (1990-2020)	82
	3.16(d)	Average snow cover (in %) in Dangme Chu Basin for December (1990-2020)	82
	3.17	Vegetation area changes with elevation from 1990-2020 for the Manas-Beki basin	83
	3.18	Snow cover area changes with elevation from 1990-2020 for the Manas-Beki basin	83
	3.19	Snow and vegetation area changes with elevation for the overlap region in upper Manas-Beki basin, 1990-2020	84
4	4.1	Flowchart of overall methodology used for mapping and change analysis of glaciers and high-altitude lakes in Manas-Beki basin	101
	4.2	Distribution of glaciers in upper catchment of Manas-Beki river basin based on satellite data of 2020	104
	4.3	Types of glaciers in the Manas-Beki basin	104
	4.4	Changes in glacier count and area in sub-basins of Manas-Beki river (1990-2020)	105
	4.5	Percentage change in glacier count and area in sub-basins of Manas-Beki river (1990-2020)	105
	4.6	Glaciers identified in Manas-Beki basin in 1990 and 2020 with type of changes; glacier in 1990 (a) disappeared in 2020 (a'), glacier in 1990 (b) decreased in 2020 (b'), glacier in 1990 (c) fragmented in 2020 (c')	107

4.7	Area covered by glaciers (primary axis, bars) and number of glaciers (secondary axis, lines) under different size categories in sub-basins of Manas-Beki river basin in 1990 and 2020	109
4.8	Percentage change in glacier coverage area based on different glacier sizes in Manas-Beki basin (1990-2020)	110
4.9	Glacier sizes under different elevation zones of Manas-Beki basin in (a) 1990 and (b) 2020	111
4.10	Altitudinal distribution of glacier area in the sub-basins of Manas-Beki river basin in 1990 and 2020	112
4.11	Distribution of glaciers in different aspects for the sub-basins of Manas-Beki river basin (1990 – 2020)	113
4.12	Distribution of glaciers in different slopes for the sub-basins of Manas-Beki river basin (1990 – 2020)	114
4.13	Distribution of high-altitude lakes in upper catchment of Manas-Beki river basin based on satellite data of 2020	115
4.14	Types of high-altitude lakes in the Manas-Beki basin	115
4.15	Distribution of lake types in 1990 and 2020 in sub-basins of Manas-Beki basin	118
4.16	Changes in high-altitude lakes for sub-basins of Manas-Beki basin (1990-2020)	119
4.17	Altitudinal distribution of high-altitude lakes in sub-basins of Manas-Beki basin (1990-2020)	119
4.18	Monthly mean temperature (⁰ C) during monsoon season from 1990 to 2020 in sub-basins of Manas-Beki river basin	121
4.19	Monthly mean temperature (⁰ C) during winter season from 1990 to 2020 in sub-basins of Manas-Beki river basin	122
4.20	Monthly total precipitation (mm) during monsoon season from 1990 to 2020 in sub-basins of Manas-Beki river basin	123

4.21	Monthly total precipitation (mm) during winter season from 1990 to 2020 in sub-basins of Manas-Beki river basin	124
------	---	-----

ACRONYMS

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
DEM	Digital Elevation Model
ECMWF	European Centre for Medium-Range Weather Forecasts
ESA	European Space Agency
ETM	Enhanced Thematic Mapper
GEE	Google Earth Engine
GIS	Geographical Information System
GLI	Glacial Lake Inventory
GLIMS	Global Land Ice Measurements from Space
GLOF	Glacial Lake Outburst Flood
JAXA	Japan Aerospace Exploration Agency
LISS	Linear Imaging Self-scanning Sensor
LULC	Land Use and Land Cover
MBT	Main Boundary Thrust
MIR	Mid Infra-Red
MSI	Multi-Spectral Instrument
NASA	National Aeronautics and Space Agency
NDSI	Normalized Difference Snow Index
NDVI	Normalized Difference Vegetation Index
NESAC	North Eastern Space Applications Centre
NIR	Near Infra-Red
NRSC	National Remote Sensing Centre
NSIDC	National Snow & Ice Data Center
OLI	Operational Land Imager
RS	Remote Sensing
SD	Standard Deviation
SOI	Survey of India
SWIR	Short Wave Infra-Red
TM	Thematic Mapper
USGS	United States Geological Survey