Utilizing Riverine Ecosystem for Optimal Benefits

Synopsis Report of the Doctoral Thesis

Submitted by

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Contents

Abstract

The intrinsic value of nature provides a variety of benefits in the form of ecosystem services that support the world economy and advance social and economic well-being. Since rivers have always been an important component of the landscape, riverscapes are just as important as landscapes. Since the beginning of time, it has provided various environmental benefits to thrive life within it. The complex interdependence between humans and nature is achieved by analyzing, modelling, quantifying, and valuing the degree to which humans are connected and benefitted from the ecosystem. Ecosystem services are now poised to provide real solutions to the problem of how to sustainably manage natural resources.

In large braided river systems around the world, there are various activities carried out along the floodplain. The floods bring fresh sediments along with them and deposits downstream. This process of aggravation and deposition of sediments due to the flow of water in the river leads to the formation of sandbars. The extent and characteristics of sandbars vary over the years due to the varying river morphology, making it difficult for researchers to conduct investigations in the river. This study attempts to understand the riverine ecosystem, particularly the sandbars within the Brahmaputra River, and the economic benefit derived from its utilization in agriculture and farming activities. The Brahmaputra River exhibits complex morphological characteristics due to wider braided river width, high flow, and sediment variability with erodible banks. A two-dimensional (2D) hydrodynamic model MIKE 21C was developed to determine the area available in the sandbar under different flow conditions. It can also be understood that increased urbanization has led to diminished mainland agricultural activities. The rapidly growing populations and rising food consumption necessitate either expansion of agricultural farmlands or sufficient production gains from existing resources. Riverine sandbars provide additional fertile landmass that could support farming and agricultural practices to cope with the rising food demand amidst urbanization.

The research encompasses land-use change using historical data and geospatial information. Intensive field investigations, questionnaire surveys, and data collection were done to determine current practices within the ecosystem. The questionnaire survey revealed various aspects of economic benefits, practices of sandbar cultivation, beneficial produce, difficulties faced, and willingness among farmers to expand sandbar cultivation. Satellite images were derived at decadal scales to determine the change in the land-use land cover (LULC) within the Brahmaputra River in Assam, India. The analysis showed that the

percentage of vegetated sandbars has increased and the percentage of non-vegetated sandbars has decreased during the years 1976-80 to 2016-17. Furthermore, it was found that the area under cropland and vegetated sandbar varied seasonally. The temporal variation of the vegetation status of crops grown in different sandbars was analyzed using the Normalized Differential Vegetative Index (NDVI). The interannual variation of NDVI values indicated the change in the crop cultivation period as well as different phases of growth and shifting of cropping patterns in the sandbars of the Brahmaputra River.

The study was carried out by gathering both primary and secondary data. To study the characteristics of sediments within the sandbars, a total of 126 samples from 42 sandbar locations were collected from the surface (topsoil), sub-soil (Upto depth of 30 cm), and bottom soil (30–100 cm depth). The samples were categorized as newly formed sandbars, vegetated sandbars, and cultivated sandbars and tested in the laboratory for the presence of nutrients and minerals. The experimental observations and field studies revealed that the vegetated and cultivated sandbars consist of silty and loamy soils, favoring agriculture and the newly formed sandbars were devoid of silt and clay, which can be utilized for growing crops like groundnut and some other vegetables, which requires sandy loam or clay loam soil. Although it was seen that sandbar activities had been carried out in a few sandbars within the Brahmaputra River, however, utilizing all possible agricultural land optimally is essential to alleviate the threat of food security and for the socio-economic development of society. As crop planning involves several possible and valuable objectives, which may or may not conflict with each other, a choice of judicious cropping pattern and temporal adjustments therein may be a useful strategy to minimize the possible crop damages and maximize economic returns and productivity. The uncertainties associated with the agricultural system were also handled through inexact multi-objective fuzzy programming optimization approaches, which could enable decision-makers to plan the cropping pattern ahead of time, thereby decreasing crop damage and economic losses. A substantial component of the uncertainty in agricultural productivity comes from seasonal variability linked to inter-annual climate fluctuations. The water level fluctuations could significantly impact crop growth within the sandbars. The seasonal forecasts were helpful in farmers' decision-making process as they predicted the expected streamflow in the near future. The historical information of the recent past events provided valuable information for future flows. To evaluate the economic losses an optimally planned riverine agricultural area would suffer if the flow variation exceeds a certain threshold, a damage estimation model was developed. The model could comprehend the losses under fluctuating water level in different seasons in subsequent years that was found to vary between 5 and 34 percent in the study. With the practice of sandbar cropping and farming in riverine environments, farmers and dwellers need to understand risk and have risk management skills to better anticipate problems and reduce consequences. The study proposed a risk assessment approach for helping the decision-making process at a local level, addressing risks that affect agricultural areas near rivers, particularly the sandbars.

This study provides a framework for integrating modelling techniques with optimization approaches in an agricultural system under uncertainties within riverine ecosystems. The study shows the immense potential of utilizing the sandbars of large rivers to sustain food demands, alongside developing links between land-use change, ecosystem behaviour, and socio-economic development. The research works provide a vision towards utilizing the landmasses formed due to hydrological processes and morphological changes within the rivers around the globe that could sustain the food demand of the ever-increasing population.

Keywords: Riverine ecosystem; Mathematical modeling; Geospatial techniques; Optimization; Damage estimation; Risk assessment

1. Introduction

1.1 General

Nature's intrinsic worth delivers a wide range of advantages in the form of ecosystem services that fuel the global economy and promote human and social well-being (MEA 2005, Kumar 2010). Tourism, forestry, agriculture, and the food and beverage industries are all sustained by nature, and they provide possibilities for recreation, cultural inspiration, and spiritual fulfillment. Riverscapes are just as essential as landscapes since rivers have always been a vital part of the landscape. River transport dissolved minerals, sediment, and nutrient-rich detritus from living and dead plants and animals. The diversity of rivers varies spatially across countries as well as in different seasons. Seasonal and annual variations in the amount of sediments and nutrients carried downstream could be significant, and such depositions over time improve the river's use in a variety of ways. Near the rivers, a diverse range of flora and fauna, plants, and animals thrive. It provides environmental services that have drawn humanity to them since the dawn of time. Figure 1.1 shows a schematic diagram of human dependency on river-floodplain systems.

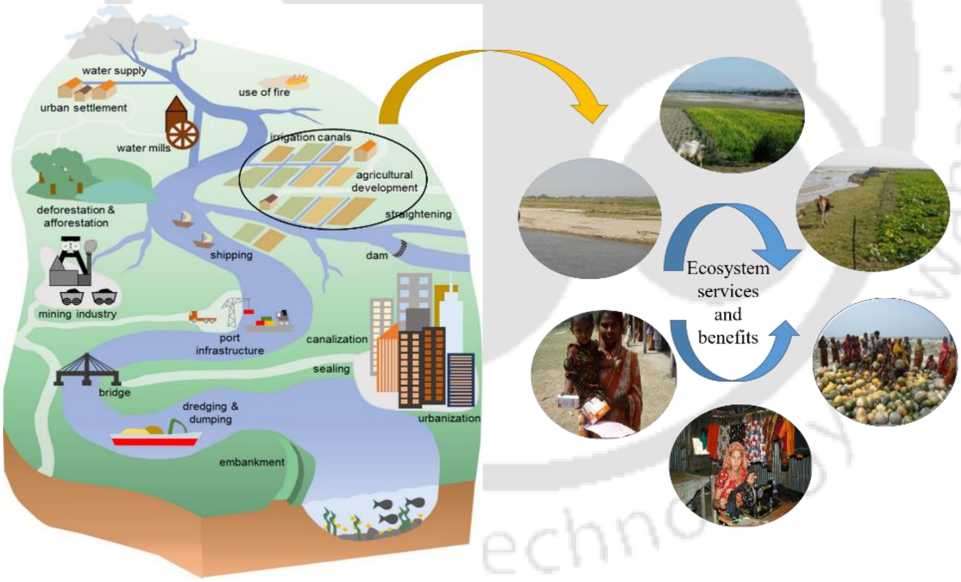

Figure 1.1: Schematic diagram of human dependency on river–floodplain systems (Maaß, 2019)

Large river systems around the world, such as the Mekong, the Brahmaputra, and the Mississippi, provide a vast array of services that benefit human well-being. The Brahmaputra is the fourth largest river in the world in terms of average flow discharge, whereas the river ranks 22nd in terms of the drainage area (Sarma and Acharjee 2018). In Assam's floodplains, it maintains a huge braiding in significant segments. Millions of people are dependent on this river for their livelihood, and land is extremely valuable within the river. The dwellers residing in the floodplains rely on the normal flood to bring fresh sediments to the floodplains favouring agriculture and farming. As such, the river has been used for a variety of purposes, including agriculture, aquaculture, grazing, transportation, drinking, and washing.

1.2 Riverine Ecosystem and its services

The riverine ecosystem encompasses ecological, social, and economic processes (ecosystem functions) that interconnect organisms (ecosystem structure), including humans, over some time period (Stanford et al., 2017). It provides a range of fundamental services to human well-being, health, livelihood, and survival (MEA 2005; de Groot et al. 2014). Ecosystem services are now poised to provide real solutions to the problem of how to sustainably manage natural resources. The Millennium Ecosystem Assessment (MEA) identified four major categories of ecosystem services: provisioning, regulating, cultural, and supporting services. Understanding these complex interactions between ecosystems and humans is important to detect the impact of changes in stressors on river ecosystems and their scope of utilization. Feeding the future world population sustainably and satisfactorily requires accessibility to resources of adequate quantity and quality (Sonneveld et al., 2018). Ecosystems provide direct provisions for humans through processes of cultivation, food, and fiber. Fisher et al. (2009) suggest that ecosystem services are the aspects of ecosystems used actively or passively to generate human well-being and do not necessarily relate to specific ecosystem functions. Therefore, there is a complex set of relationships between the intermediate services, final services, and benefits derived from ecosystems. Figure 1.2 shows the interaction of the ecosystem and its services in agricultural systems.

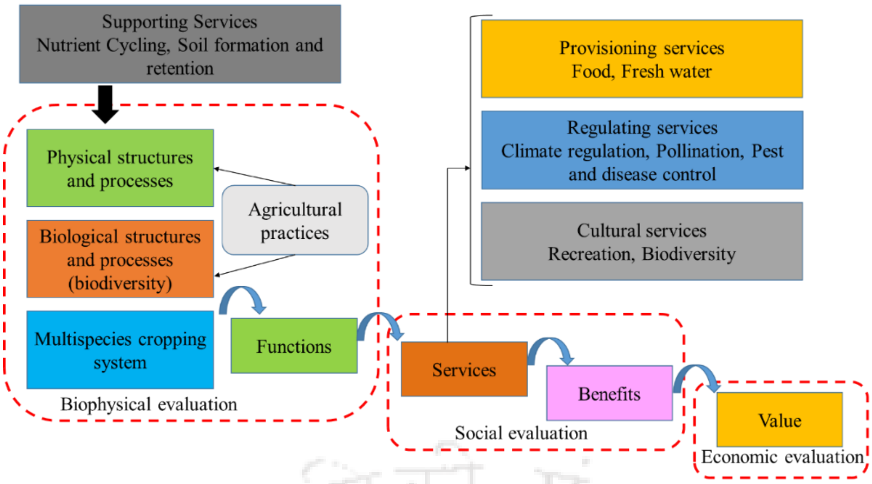

Figure 1.2: Cascade of ecosystem services in agricultural systems. Adapted from Haines-Young and Potschin (2010). The classification of services is taken from the Millennium Ecosystem Assessment (2005). "Physical structures and processes" also encompass physical and chemical structures and processes

1.3 Utilization of riverine sandbars

In large braided river systems around the world, various activities are carried out along the floodplain. The floods bring fresh sediments along with them and deposits downstream. The formation of sandbars depends on the sediment transport and flow of the river. During the flood and its recession afterward, the debris flowing with water stabilizes the sandbars to initialize the plant growth. Sandbar utilization for performing farming and agricultural activities is a unique challenge within a riverine ecosystem. Large dynamic braided rivers like the Brahmaputra River undergoes flood every year during the monsoon period and pose a certain risk to agriculture and farming activities. The huge volume of water flow and sediment deposition leads to changes in the morphology of the river. However, once the floodwater recedes, the river provides numerous opportunities for various activities. The floodplains and sandbars of the river are inhibited by the poor community, who are dependent primarily on agriculture for their livelihood (Chakraborty, 2013). Nevertheless, the proper utilization of such resources is complex and needs to be dealt with optimally, considering the seasonal and spatial land variability. Moreover, increased urbanization has led to diminished land availability for agricultural activities. To meet the increasing demand for food, agricultural production needs to be increased. Many researchers have emphasized that water, energy, and food are under stress, and their demand will increase significantly in the upcoming decades (El-Gafy et al., 2017; Endo et al., 2015). Agriculture is the prime user of land and water resources, essential for food production (Sadeghi et al., 2020), and its sustainability requires efficient management of these resources in an optimal way (Garg and Dadhich, 2014).

1.4 Motivation of the study

It is commonly accepted that the ecosystem's services help society in terms of well-being; however, how these advantages are divided in society is yet unknown. The ability of offered services to improve human well-being is dynamic and path dependent. Rural livelihoods are diverse in geography and time, and rural communities rely on a variety of ecosystem services to make a living. The Brahmaputra River flowing through Assam gives numerous chances and has become a source of income for a variety of people. Its sediment loads and transport patterns have an impact on the region's ecology and agriculture. Thousands of hectares of sandbars emerge every year after the monsoon when the water level in the rivers reduces. The extent and characteristics of sandbars vary year to year due to the unpredictable geomorphology of rivers, making it difficult for researchers to conduct investigations in the river. As a result, utilising this riverine land for diverse activities for the welfare of mankind is critical and should be investigated. Hydro climatic disturbances could adversely affect the agricultural systems within the ecosystem. Excess water could lead to flooding of the entire crop area, and scanty rainfall could lead to drought-like conditions. The changing flow conditions, extreme events, frequency, and magnitude of floods due to streamflow variation could cause challenges to farmers and threaten food security.

To address the challenges faced while utilizing the sandbars, the thesis work encompasses land-use change using historical data and geospatial information. Intensive field investigations, questionnaire surveys, and data collection were done to determine current practices within the ecosystem. Because of the large land mass within the river's planform, a more planned strategy to utilize these sandbars is required to get maximum advantage while minimizing disruption to the river's ecology. As a result, an optimum framework for allocating land for agricultural, farming, and non-farming uses has been devised. The streamflow parameter is significant for crop planning, and crop damage since the riverine ecosystem is surrounded by water bodies. The development of better and more reliable numerical methodologies, efficient computing power, and innovative topographic survey techniques has envisaged the reliability on modeling studies. The creation of a damage assessment model has made it possible to analyze agricultural damage caused by water level fluctuations in a systematic way. To address the challenges faced while utilizing the sandbars, the work also focuses on the social and economic aspects of the riverine ecosystem to derive the benefits. The model assesses the actual benefit obtained from the agricultural planning process after accounting for potential economic losses. While undertaking agricultural activities in sandbars, there always exists a potential danger of crop damage due to unpredictable streamflow conditions. However, forecasting approaches and statistical procedures, which have been principally detailed in the research work, can be utilized to predict future events and reduce the severity of such risks to some extent.

1.5 Research objectives

Studies on the sandbars of the Brahmaputra River are limited, and they are required to draw considerable advantages, taking into account land use, challenges faced by dwellers, present practices, generated benefits, and other pertinent factors. Based on the necessity of the research, the following objectives are formulated.

1. Hydrodynamic model study of a riverine ecosystem to understand impacts of temporal variation in flow.

2. Socio-economic study of dwellers residing within the floodplain of a large river system and their challenges in adaptation to climate change.

3. Development and application of optimization model for land-use planning in general and riverine ecosystem in particular.

2. Study area and data acquisition

2.1 Description of the Study area

The Brahmaputra River is a dynamic braided river originating from the Manasarovar Lake in the Kailash range of the Himalayas. It is a transboundary river flowing through Tibet, India, and Bangladesh, meeting the Ganga River in Bangladesh, and finally falling into the Bay of Bengal. The river basin extends over a catchment area of 5,80,000 Sq. Km lying in Tibet, India, Bangladesh, and Bhutan. In Assam, the Brahmaputra River lies between 95°23’5.94” to 89°49’14.29” East longitudes and 27°49’15.82” to 25°43’40.38” North latitudes. It flows for about 670 km in Assam along an alluvial valley as a wide braided river drained through many varied and diverse habitats across its course. Assam is considered as the land of agriculture, and more than 60% of the population is engaged in this region. Agriculture and its allied sectors play a pivotal role in socio-economic development as it provides livelihood to a major portion of the population. The sector supports more than 70% population of the state by employing more than 53% of the workforce (https://des.assam.gov.in/documents-detail/economic-survey). The cropping season is mainly divided into two periods: The Kharif period from July-October and Rabi period from October-March. The period between March and June is called Zaid, and summer crops are grown. The farmers follow single and double cropping systems of farming practice in all three seasons. Among all crops, rice is the dominant crop grown across all districts, contributing to about 80% of the gross cropped area. The average annual rainfall is about 2000mm, which provides adequate standing water for rice growth (Talukdar et al., 2004). Pulses are other important crops grown in Assam during the Rabi period. However, certain other pulses are also grown in some other districts during the Kharif season. Black gram, green gram, linseed, lentil, peas, beans, etc., are farmed extensively in Assam. Crops such as jute, pea, potato, wheat, and vegetables are grown under different cropping techniques.

In the present work, the study region lies within the Brahmaputra River extending from Majuli upstream to Dhubri downstream (Fig. 2.1). Two agricultural sandbars in the Barpeta district and Kamrup district of Assam were selected to understand the present cropping practices and study the potential of selective cropping approaches for agricultural economic benefits.

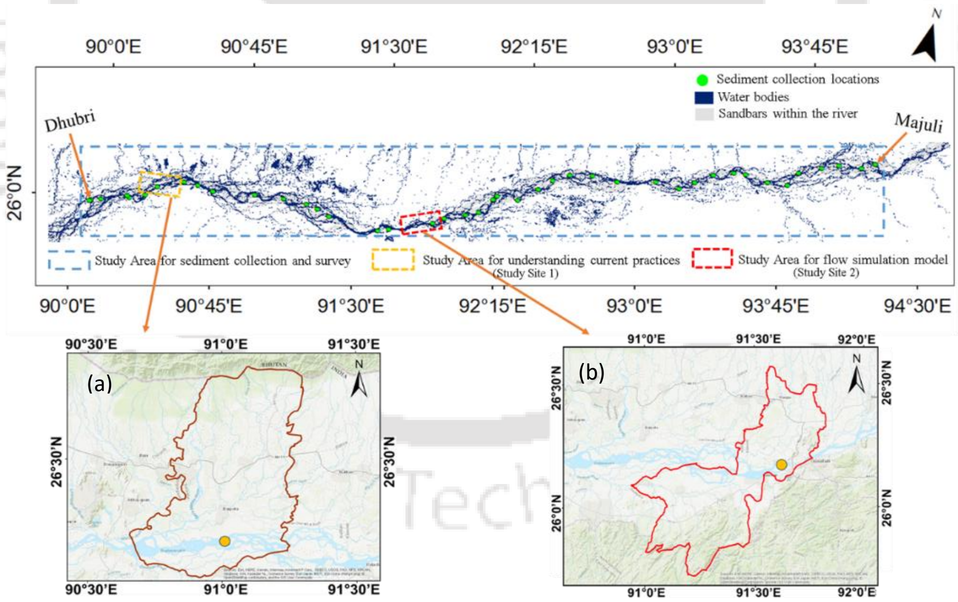

Figure 2.1: Study area showing the Brahmaputra River in Assam, India. (a) Barpeta district; (b) Kamrup district

2.2 Data acquisition

The research work was initiated by carrying out a satellite-based study, followed by field investigations and questionnaire surveys that provided details about the type of crops cultivated within the sandbars, the pattern of cropping, age of farmers, duration, profit, production, etc. The detail of the crop types, crop yield, production, and cultivation cost were also derived from primary and secondary data. The primary data was collected from various households of dwellers and farmers practicing sandbar cultivation. The secondary data was collected from various government and non-government sources. The official reports, records, journals, and publications of agencies such as FAO, World Development Report, Asian Development bank, Census of India, Government of India economic survey, Department of Agriculture and Co-operation, Ministry of food and agriculture, Planning Commission, Directorate of Economic and Statistics, Govt. of Assam, Directorate of Agriculture, Assam, etc. formed the data source. For the geospatial study, satellite imageries of the Brahmaputra River were collected for the years 1976–80, 1993–95, 2003–04, 2008–11, and during the flood period of 2016-17. Temporal variations to determine cropping patterns over the years were monitored using the NDVI (Normalized Difference Vegetation Index) and NDWI (Normalized Difference Water Index) analysis.

3. Methodologies

3.1 Mapping agricultural activities and their temporal variations in the riverine ecosystem

The unsupervised classification approach was applied to develop the land cover map of the study area and highlight the land-use land cover changes (LULC) in the area corresponding to different classes, i.e., Waterbody, Dry Sandbar, Cropland, and Vegetation at a decadal basis from 1976-80 to 2016-17. The classification aims to understand the pattern of changes in the sandbar areas from barren to vegetation to cropland, which provides information about the sandbars being utilized and the changes in their area. For evaluating the performance of the classification, an accuracy assessment was performed for the observed changes in the LULC by formulating the error/confusion matrix. Two vegetation indices, NDVI and NDWI, were used to determine the interannual variations in the cropping patterns. NDVI was used to understand the changes in the vegetation cover, and NDWI was used to monitor the moisture conditions of vegetation cover.

3.2 Hydrodynamic model study on riverine ecosystem

To determine the water depth in the sandbar areas considered for the study, a two-dimensional (2D) hydrodynamic model, MIKE 21 C, was set up with river bathymetry and simulated at different discharges. MIKE 21C is a generalized mathematical modelling system for simulating the hydrodynamics of two-dimensional (2D) surface flow and sediment transport using a rectilinear or a curvilinear grid (DHI, M., 2011). The simulations were carried out on the curvilinear grid generated over the entire area. This model solves the fully dynamic and vertically integrated Saint Venant Equation (continuity and momentum equation) in two directions. The model incorporated the discharge parameters and their corresponding water level as the boundary conditions. For the model simulation, the streamflow data was obtained from the Pandu gauging station from 1999 to 2015. The response to different flow conditions was analysed, and sandbar areas available at different cropping periods were determined. The model was calibrated with the velocity measured at the downstream section of the river.

3.3 Sediment analysis to understand the sandbar dynamics

To study the characteristics of sediments within the sandbars, a field survey was performed from Majuli upstream to Dhubri downstream. A total of 126 samples from 42 sandbar locations were collected from topsoil (surface), subsoil (up to a depth of 30 cm from the surface), and bottom soil (from 30-100 cm depth) and tested in the laboratory. The samples were categorized into newly formed sandbars, vegetated sandbars, and cultivated sandbars. The sediment size analysis was carried out using the Particle Size Analysis (PSA) test, and the analysis for the presence of minerals and nutrients was conducted in the laboratory using the X-Ray Diffraction (XRD) and Energy-Dispersive X-Ray Spectroscopy (EDX) tests.

3.4 Short-term flow forecasting and trend analysis for decision making

Streamflow forecasting for agricultural crop planning within a riverine system is crucial for enhancing production, understanding the risks of cropping, and improving the socio-economic condition of marginalized communities. In this study, short-term streamflow forecasting for different cropping seasons was projected using the Historical Analogue (HA), Persistence Forecast (PF), and Artificial Neural Network (ANN) approaches. The HA approach takes into account the streamflow sequences in the historical record and records similar to those that occurred recently, which may provide useful information about future flows. The PF approach uses the flow anomaly of the most recent observed month to forecast for the next 1 or 3 months. The trend analysis of the streamflow was performed using the Mann Kendall (MK) test and Sen’s slope estimator for understanding the changes in the monthly and annual time-scale. The streamflow forecasts for the future years (2016-2021) were carried out for the three seasons.

3.5 Optimization approaches to increase agricultural benefit and crop production

The optimization techniques concerning the economic benefit and loss due to the submergence of agricultural land in riverine sandbars and floodplains are of prime importance. The farmers' perspective on such cropping practices plays a significant role, which has been incorporated into the model development. Three scenarios of optimal cropping patterns were considered during the analysis: (1) comparison between the existing cropping pattern and the optimal cropping pattern in the Barpeta district; (2) determining the optimal cropping pattern by considering the fluctuating water level and selective cropping approach, and; (3) determining the optimal cropping pattern to maximize crop production and net agricultural economic benefit under fluctuating water level by accounting the uncertainties. The fuzziness associated with the system, such as fluctuation in market prices, crop yield, food demand, cost of cultivation, etc., are highly uncertain. These uncertainties expressed as interval numbers, fuzzy objectives, and constraints were solved using the Inexact Multi-Objective Fuzzy Linear programming (IMOFLP) approach.

3.6 Damage estimation for determining agricultural economic losses

The complexities in cropping were incorporated based on the observed streamflow and the cropping pattern subject to survivability under different depths. To address the complexities involved and challenges associated in determining the flood loss in an agricultural ecosystem, a damage estimation model was developed. The model determines the losses suffered due to crop damage under fluctuating water levels while performing agriculture activities in riverine sandbars. The objective was to see if an optimal cropping pattern was planned based on the average streamflow value and if the same pattern is implemented over the years, what could be the extent of crop damage the farmers may experience due to flow variation. While formulating the damage estimation model, the damage to crops was addressed at different levels/stages of water depth. A damaging depth is considered wherein the water level above and below this depth would result in damage to crops (Fig. 3.1). The slope of the sandbar area is gradual as the distance increases from the river toward the dryland areas. Thus, the crops suffer damage with the gradual rise in water level and also suffer damage when the water level reduces from the defined depth stages.

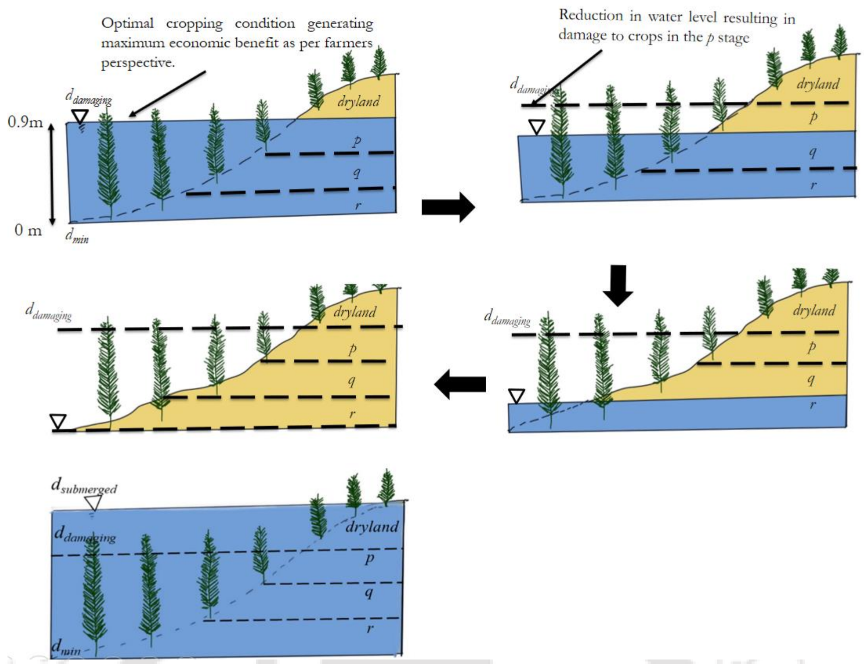

Figure 3.1 A schematic illustration of the process of damage suffered at different stages of water level variability and area available at different time scales. *p,q,r* varies between damaging depth to minimum depth.

3.7 Agricultural risk assessment

Flooding is a frequent phenomenon occurring in areas near floodplains as well as low-lying riverine areas. In this study, flood frequency analysis was performed to predict the flow values corresponding to different return periods. The statistical data were used to construct the frequency distributions, and goodness of fit tests were performed using parameter estimation. The discharge, probability of exceedance, and loss were associated by developing a relationship between discharge-frequency curves and loss-discharge curves. The damage at different depths was estimated by developing a damage factor, and the total seasonal losses were calculated. The adaptation strategies to flood events were also discussed in the study.

4. Results and Discussions

4.1 Mapping agricultural activities and their temporal variations in riverine ecosystem

The LULC classification performed on a decadal scale for the entire Brahmaputra River, across an average area of around 7,50,000 ha from Majuli to Dhubri, found that the percentage of dry sandbars remains more or less unchanged, occupying around 25-30% of the entire area. However, the cropland area can be seen decreasing from 25% to 11%, and vegetation cover increasing from 20% to 25% over the years. To further analyse the cropland area and vegetation cover changes, the study was conducted on a sandbar area of approximately 37,117 Ha in the Barpeta district for two different years. During the pre-monsoon period in 2016, about 35% of the sandbar was found to be dry sandbar, and about 28% were utilized for agriculture activities as cropland. While in the year 2019, about 27% of sandbars were dry sandbars, and the cropland area covered about 39% of the total area. This indicated a decrease in the dry sandbar areas by around 23% and an increase in the cropland area by around 36%. During the post-monsoon season, dry sandbar covered about 24% and 31% area, and cropland covered about 24% and 27% area in 2016 and 2019, respectively. From this analysis, it can be inferred that dry sandbars within the riverine ecosystem are being utilized for cropping and other agricultural activities, with an increase of around 24% of the cropland area during the period of 2016 to 2019. The interannual variation of NDVI values also showed the practice of double cropping in the sandbars of the Brahmaputra River. However, while conducting field visits, it was found that the traditional cropping approach was practiced in the sandbars, and large areas were left barren. Thus, the study incorporated optimization approaches for generating maximum profits through optimal crop planning.

4.2 Hydrodynamic model study on riverine ecosystem

The simulation results exhibit the water depth under varying streamflow along with current speed across the study reach. It was found that the velocity ranged between 0.1-0.4 m/sec in the sandbar portion while it ranged above 1.4m/sec in the river portion. It can also be seen that during the low flow period, there are large sandbars formed that could be utilized for agricultural activities. The results showed that the area available during the Zaid period was more compared to Rabi and Kharif periods. As the water level was high during the Kharif period, the sandbars were generally left unutilized. However, crops such as Jute and flood-resistant varieties of paddy could survive the flood conditions.

4.3 Sediment analysis to understand the sandbar dynamics

During the experimental analysis, it was found that the sediment collected from the vegetated sandbars contained around 45-50% of silt and clay, whereas the sediments collected from cultivated sandbars contained 30-40% of silt and clay. The sediments from the cultivated and vegetated sandbars were well-graded, indicating that these sandbars were suitable for the growth of various crops. The XRD analysis showed the presence of Feldspar, Zircon, Monazite, and Quartz, which are considered key nutrients for crop growth and health. . Feldspar consists of Calcium (Ca), Sodium (Na), and Potassium (K), which are key nutrients required for plant growth. Na and K play a vital role in osmotic regulation in plants. Silicates are present in Zircon, which increases crop productivity and provides resistance to pathogens, insects, and pests. Quartz is the most common crystalline form of silica (Silicon Dioxide). Silicon improves the defense against biotic constraints in the form of plant pathogens. The EDX analysis showed the presence of Boron, Oxygen, Silicon, and Carbon in higher amounts by weight percentage (>10%). The percentage of Oxygen (O), Carbon (C), and Silicon (Si) were found to be more than 20% when compared with other elements (Fe, Mg, Al, Ti, Ca, Cu, K, and N) in the samples. The presence of certain minerals like Boron and Monazite indicated the use of fertilizers for crop growth. The concentration of macronutrients, Nitrogen (N) and Potassium (K) were below 2% during our analysis, which concurs the need to apply additional fertilizers for plant growth and physiological functioning.

4.4 Short term flow forecasting and trend analysis for decision making

During the flow forecasting, it was found that the Historical Analogue method performed well in forecasting the streamflow during the Rabi and Zaid periods. However, during the Kharif period, both the methods could not capture the fluctuations in the flow of the recent past. Therefore, to overcome the difficulties, the ANN model was applied in the study to handle the complexities. The results highlight that the ANN approach effectively handled the complexities of forecasting the streamflow during the high flow period. Based on the forecasted streamflow, the hydrodynamic model generated the water depth at different stages considered during the study. The area available under different depths was determined, and it was found that the maximum area was available during the Zaid period in the sandbars. From the study of trend analysis for the years 1999-2015, a significant rise in streamflow during the month of December till February was seen. This time period corresponds to the low flow in the river, which tends to show an increasing trend in the streamflow. The streamflow during June-November showed a downward trend, though is non-significant at a 5% significance level. This corresponds to the high flow period witnessed at the Pandu station in the Brahmaputra River. The highest rate of the significant increasing trend was observed in the month of February (+69.41 m^3/s/year). The highest rate of non-significant increasing and a decreasing trend was observed during the months of March (+100.35 m^3/s/year) and September (-240.69 m^3/s/year), respectively.

4.5 Optimization approaches to increase agricultural benefit and crop production

Three aspects of optimal cropping patterns were considered. The first aspect compares the existing cropping pattern in the Barpeta district with the optimal cropping pattern derived from the linear programming model. The second aspect involves developing a constrained linear programming problem to determine the optimal cropping pattern by considering the fluctuating water level in the riverine sandbar of the Kamrup district. The third aspect deals with determining the optimal cropping pattern by maximizing crop production and net economic benefit under fluctuating water levels considering uncertainties existing in the crop planning system. For the first scenario, the optimal cropping pattern highlighted a significant reduction of the overall rice area by 8% and an increase in fibers, cereals, and vegetables by 7% annually. The area under fibers and cereals increased by 1% and 2%, respectively. Potato and vegetable area increased to 6% and 13% of the cultivable area from 4% and 9%, respectively. However, the area under Pulses remains equivalent at 5% of the cultivable area. The optimization model suggested a diverse cropping pattern with an additional benefit of ~15%. The highest net benefit was obtained from the cultivation of vegetables, followed by Winter Rice, Summer Rice, and potato. Eco camps and various festivals in the sandbars for the tourists were an additional source of income generation. For the second scenario, an additional benefit of ~20.6% was achieved during the selective approach of cropping in the Zaid period. Similar observations were also found for the Rabi and Kharif periods, with increased benefits of ~35.17% and ~18.4%, respectively. The model witnessed an allocation of around 0.5% of the total area available towards ahu and boro paddy cultivation during the Zaid period. The area allocated towards dairy farming was nearly 3%, and it generated a net benefit of around 19.6%. Among paddy cultivation, the maximum allocation of the land area was found to be about 9% for sali paddy during the Rabi period, about 6% for deep-water (DW) paddy in the Rabi period, and about 3% for Bao paddy during the Kharif period. The net benefits determined by the model under the optimal cropping pattern were found to be around 130.25 million rupees during the Zaid period, around 52.85 million rupees during the Kharif period, and around 98.59 million rupees during the Rabi period. The IMOFLP approach provided a range of alternative solutions for the farmers and decision makers (DM) at different levels of satisfaction. The net benefit was found to vary between a range of Rs. $[1.27, 3.13] \times 10^8$, and the crop production was found to vary between $[16.4, 20.8] \times 10^6$ Kg using the IMOFLP approach, while the crisp optimization approach provided a net benefit of Rs. 1.35×10^8 and crop production of 12.9×10^6 Kg. Therefore, it can be seen that the constrained LP approach provided a deterministic value with one possibility of outcomes, whereas the IMOFLP approach provided stable decision alternatives to the farmers and decision-makers.

4.6 Damage estimation for determining agricultural economic losses

The damage estimation was carried out based on the optimal depth considered as a threshold water level (maximum depth at which crops survive), above and below which the crops suffer damage. The objective was to determine the losses based on the seasonal variation in streamflow, starting from time, t to time, t+k. "t =1" represents the first year, i.e., 1999 in our study, and t+k represents the year lagged by k^{th} year, and k can take any value depending on the availability of flow data. We have considered up to 2015 in this study. Thus, the net benefits obtained in the next time period would vary from those derived from the optimal cropping pattern. For the considered time series during the Zaid period, the maximum loss accounted was about 34.5% in 2010 when compared with the expected benefit. Similarly, the maximum losses during the Rabi and Kharif periods were about 24.4% in 2012 and about 14.4% in 2013, respectively. While determining the stage-wise losses at the considered depth stages in the study, it was found that the maximum loss of about 31.1% and 20% were suffered in the dryland areas in the Zaid and Rabi period, respectively, and a maximum loss of about 6.8% was suffered in the depth range of 0-0.3m.

4.7 Agricultural risk assessment

While performing the risk assessment, two scenarios were considered; (S1) when the water level decreases from the damaging depth, and (S2) when the water level increases from the damaging depth up to the submerged depth. At depths above the damaging depth, the crops suffer losses at subsequent stages, and a damage factor is associated with the depth. The losses corresponding to the rising water level would generate a substantial amount of losses. Therefore, the expected benefit would differ from the actual benefit derived from the optimal cropping pattern under the fluctuation streamflows in different seasons. Fig. 4.1 shows the relationship between the (a) Loss-discharge (b) Loss-depth for scenario S1, (c) Loss discharge, and (d) Loss-depth, for scenario S2, for the Zaid period.

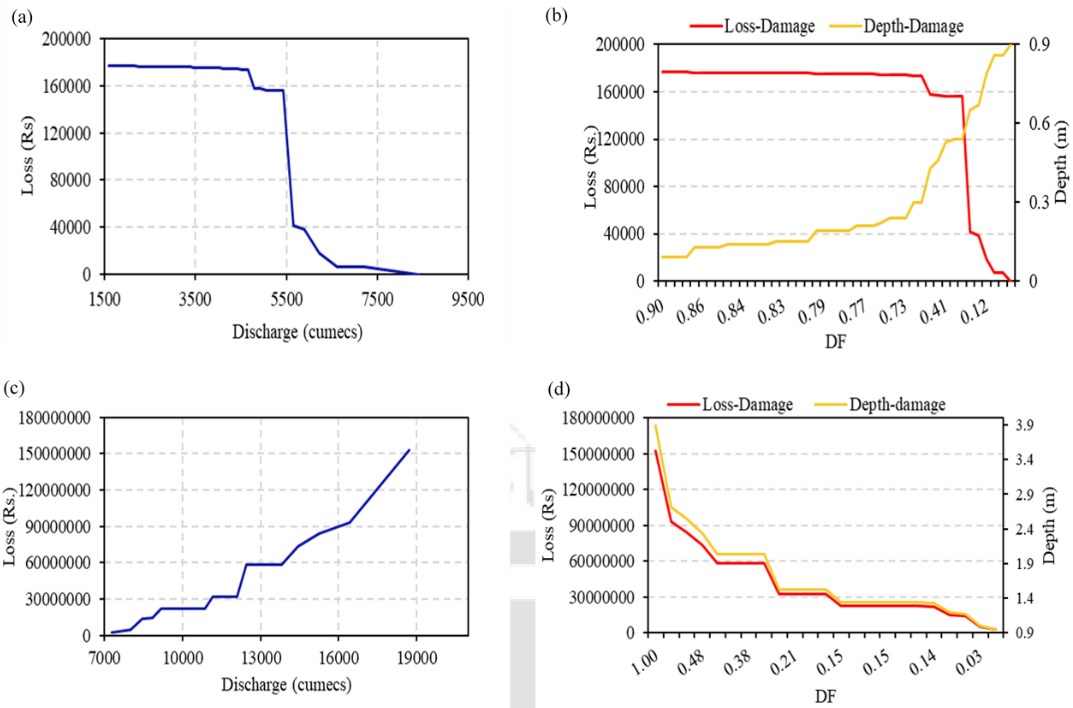

Figure 4.1 Relationship between the depth and loss during the Zaid period

5. Conclusions and Recommendations for future work

The study revealed the scope and utilization of these sandbars for various agricultural activities and also envisaged the necessity to make people understand the need for the socio-economic development of society. This preliminary study attempted to understand the cropping practices, patterns, and suitability in River Brahmaputra's sandbars. Both the primary and secondary data obtained gave detailed information about agricultural activities in riverine sandbars. The satellite imageries over the areas of interest could provide vital information about the land-use land cover changes over time, and in-situ data were required to understand the cropping practices followed, crops grown, duration, and season of cropping in the riverine sandbars. The sediment analysis for the type of soils and the feasibility of such soils for crop growth and their mineral and nutrient content revealed important soil information for crop growth. As the sandbars exist near the rivers, the study on variations in the water level and changing streamflow during different crop growth seasons were achieved using flow simulation model. The findings of the study revealed new insights into the flow dynamics of large braided rivers. From the HD model, the sandbar area available under varying water depths, during different seasons was determined for planning agricultural activities. Seasonal forecasts were helpful in farmers' decision-making process as they predicted the expected streamflow in the near future. Trend analysis provided relevant information regarding future crop planning, and forecasted streamflows could be incorporated in assessing the risk of agriculture practice and minimizing the damage. Optimal cropping patterns suggested diverse crop planning ensuring increased benefits as compared to the existing patterns. Agricultural and farming activities within the riverine ecosystem involved risks to crop damage with economic loss, which could be minimized up to certain extent with the approaches depicted in the study. Therefore, this study presents an overall understanding of the agricultural practices and the derived benefits and associated losses in riverine sandbars through a conceptual framework.

As a future extension of the current research, the scope of the study is discussed as follows:

- Satellite imageries from like Landsat 7 and 8 provide information about the changes and phenological characteristics of crops grown in the sandbars. However, to distinguish between different crop types, finer resolution imageries are needed that could provide detailed information on crop health as well.
- The study was carried out in the Brahmaputra River; however, the study could be extended to different rivers around the world, as the sediment characteristics could vary widely.
- The damage estimation model developed in the study could handle the crop damage suffered due to water level fluctuations during different seasons. However, there is scope to improve the model by incorporating the maximum number of flood or dry days and determining the extent of crop damage suffered.
- In the optimization model, economic benefits through agricultural practices in sandbars were considered. However, maximizing benefit by incorporating the profit earned through sand mining used as a construction material could be considered as a scope for future work.
- The downstream impact of the potential risk of using fertilizer on water quality and the self-purification capacity of rivers is necessary to understand. An ecological model could be developed and linked with the optimization model to better understand the impacts on the aquatic species in the future.

Selected References

Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R.V. Oneill, J. Paruelo, R. G. Raskin, P. Sutton, and M. van den Belt. (1997). The value of the world's ecosystem services and natural capital. Nature 387 (6630): 253–260.

Chakraborty, G. (2013). Assam's hinterland: Society and economy in the Char areas.

de Groot, R., L. Brander, S, van der Ploeg, R. Costanza, F. Bernard, L. Braat, M. Christie, N. Crossman, A. Ghermandi, L. Hein, S. Hussain, P. Kumar, A. McVittie, R. Portela, L.C. Rodriguez, P. ten Brink, and P. van Beukering. (2012). Global estimates of the value of ecosystems and their services in monetary units. Ecosystem Services 1: 50–61. https://doi.org/10.1016/j.ecoser.2012.07.005

DHI, M. (2011). 11. A Modelling System for Rivers and Channels. Reference Manual. DHI Water & Environment, Denmark.

El-Gafy, I., Grigg, N., and Waskom, R. (2017). Water-Food-Energy: Nexus and Non-Nexus Approaches for Optimal Cropping Pattern. Water Resources Management, 31(15), 4971–4980. https://doi.org/10.1007/s11269-017-1789-0

Endo, A., Burnett, K., Orencio, P. M., Kumazawa, T., Wada, C. A., Ishii, A., Tsurita, I., Taniguchi, M. (2015). Methods of the water-energy-food nexus. Water (Switzerland), 7(10), 5806–5830. https://doi.org/10.3390/w7105806

Fisher, B., R.K. Turner, and P. Morling. (2009). Defining and classifying ecosystem services for decision making. Ecological Economics 68 (3): 643–653. https://doi.org/10.1016/j.ecolecon.2008.09.014

Garg, N. K., and Dadhich, S. M. (2014). Integrated nonlinear model for optimal cropping pattern and irrigation scheduling under deficit irrigation. Agricultural Water Management, 140, 1–13. https://doi.org/10.1016/j.agwat.2014.03.008

Haines-Young, R., & Potschin, M. (2010). The links between biodiversity, ecosystem services and human well-being. Ecosystem Ecology: a new synthesis, 1, 110-139.

Kumar, P. (ed) (2010) The Economics of Ecosystems and Biodiversity (TEEB) – Ecological and Economic Foundation. Earthscan, London and Washington.

Lead, C., Kumar, P., Brondizio, E., Elmqvist, T., Gatzweiler, F., Gowdy, J., & Reyers, B. (2009). The Economics of Ecosystems and Biodiversity. The Ecological and Economic Foundation. Earthscan, London and Washington DC.

Maaß A-L (2019) Looking back, looking forward: Human impacts on fluvial morphodynamics since the Industrial Revolution and the return to a natural morphological river state, Dissertation. https://doi.org/10.18154/RWTH-2019-08256

Millenium Ecosystem Assessment (MEA) (2005). Ecosystems and Human Well-Being: Biodiversity Synthesis. World Resource Institute, Washington, DC.

Nicholls, R. J., Hutton, C. W., Adger, W. N., Hanson, S. E., Rahman, M., & Salehin, M. (2018). Ecosystem services for well-being in deltas: integrated assessment for policy analysis. Springer Nature. https://doi.org/10.1007/978-3-319-71093-8

Sadeghi, S. H., Sharifi Moghadam, E., Delavar, M., and Zarghami, M. (2020). Application of water-energy-food nexus approach for designating optimal agricultural management pattern at a watershed scale. Agricultural Water Management, 233(August 2019). https://doi.org/10.1016/j.agwat.2020.106071

Sarma, J. N., & Acharjee, S. (2018). A study on variation in channel width and braiding intensity of the Brahmaputra River in Assam, India. Geosciences, 8(9), 343. https://doi.org/10.3390/geosciences8090343

Sonneveld, B. G., Merbis, M. D., Alfarra, A., Ünver, O., & Arnal, M. F. (2018). Nature-based solutions for agricultural water management and food security. FAO Land and Water Discussion Paper, (12).

Stanford, J. A., Alexander, L. C., & Whited, D. C. (2017). Riverscapes. In Methods in Stream Ecology, Volume 1 (pp. 3-19). Academic Press. https://doi.org/10.1016/B978-0-12-416558-8.00001-9

Talukdar, N.C., Bhattacharyya, D., Hazarika, S. (2004). Soils and Agriculture. In: Singh, V.P., Sharma, N., Ojha, C.S.P. (eds) The Brahmaputra Basin Water Resources. Water Science and Technology Library, vol 47. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-0540-0_4.

List of publications

Journals

Gaurav Talukdar, Arup Kumar Sarma, and Rajib Kumar Bhattacharjya. "Integrating optimization and damage estimation to increase economic benefit and ensure food security under seasonal land variability." *Journal of Environmental Management* 320 (2022): 115872. https://doi.org/10.1016/j.jenvman.2022.115872

Gaurav Talukdar, Arup Kumar Sarma, and Rajib Kumar Bhattacharjya (2021). Sediment analysis and modelling based approach for optimal allocation of riverine sandbar for socio economic benefits. *Ecological Engineering*, Elsevier, 173, 106415. https://doi.org/10.1016/j.ecoleng.2021.1064152

Gaurav Talukdar, Arup Kumar Sarma, and Rajib Kumar Bhattacharjya (2020). "Mapping agricultural activities and their temporal variations in the riverine ecosystem of the Brahmaputra River using geospatial techniques". *Remote Sensing Applications: Society and Environment*, Elsevier 20, 100423. https://doi.org/10.1016/j.rsase.2020.100423

Gaurav Talukdar, Arup Kumar Sarma, and Rajib Kumar Bhattacharjya (2022). "Assessment of Land use change in riverine ecosystem and utilizing it for socio-economic benefit." *Environmental Monitoring and Assessment*, Springer, Manuscript No.: EMAS-D-21-04214. (*accepted*)

Gaurav Talukdar, Rajib Kumar Bhattacharjya, and Arup Kumar Sarma. "Optimal cropping pattern based on short-term streamflow forecasts to improve agricultural economic benefits and crop productivity under uncertainties" *Hydrological Sciences Journal*, Taylor and Francis (*Under Review*). Manuscript No.- HSJ-2022-0213

Gaurav Talukdar, Rajib Kumar Bhattacharjya, and Arup Kumar Sarma. "Understanding the effect of long-term and short-term hydrological components on landscape ecosystem" *Ecological Informatics*, Elsevier (*Under Review*). Manuscript No.-ECOINF-D-22-00708.

Gaurav Talukdar, Rajib Kumar Bhattacharjya, and Arup Kumar Sarma "Agricultural risk assessment to estimate the potential economic loss in floodplains of Large Rivers." *(Under Preparation*)

Conference Presentations/proceedings

Gaurav Talukdar, Arup Kumar Sarma, and Rajib Kumar Bhattacharjya. "Riverine ecosystem for socio economic development" 15th IHE PhD Symposium for Collaborative Water Resources Management for a Water Secure World organized by IHE Delft Institute for Water Education, 14-15 October 2021, Netherlands

Gaurav Talukdar, Rajib Kumar Bhattacharjya and Arup Kumar Sarma, Effect of Long-Term and Short-Term Hydrological Components in Riverine Sandbars. AGU Fall meeting 2022, Chicago, IL, USA, 12 - 16 December 2022