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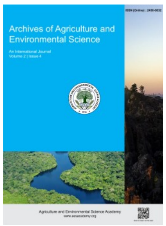

ORIGINAL RESEARCH ARTICLE

Environmental and human factors affecting Indian major carps' spawning in Halda River, Bangladesh

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ABSTRACT

The spawning success of Indian major carps (IMCs) in the Halda River is intricately linked to favorable environmental and hydrological conditions, which have shown significant variability in recent years. This research aimed to investigate the environmental and anthropogenic factors driving to decline in IMC spawning and propose sustainable management strategies. Field investigations were conducted across four key spawning sites, analyzing hydrological parameters, climatic trends, and anthropogenic influences. Results revealed a sharp decline in IMC spawning success in the year 2021, with egg production dropping to 8,580 kg and fry yield to 105.73 kg which reductions of 66% and 73.3%, respectively, compared to 2020. Key environmental stressors included rising temperatures (contributing 90% of observed variation), reduced rainfall (86%), decreased hill water runoff (84%), and saline intrusion (76%). Anthropogenic disturbances, such as pollution (76%), river bend cutting (80%), rubber dams' installation (78%), and abandoned sluice gates (84%), intensified these challenges. This study reveals climatic and anthropogenic impacts on IMC spawning decline in the Halda River, stressing the need for ecosystem-based conservation. These findings underscore the urgent need for targeted mitigation measures, including minimizing anthropogenic disturbances and restoring natural river dynamics, to enhance the resilience of IMC spawning habitats and ensure sustainable fisheries in the Halda River.

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INTRODUCTION

The Halda River, located in southeastern Bangladesh, serves as a crucial natural breeding ground for Indian Major Carps (IMCs). The Halda River's significance extends beyond its geographical and ecological features; it plays a pivotal role in the aquaculture sector by providing a pure gene pool that helps mitigate inbreeding depression among carp species. Historically, the Halda has been a critical source of pure genetic material, free from inbreeding depression, which has contributed to sustainable aquaculture practices across the country (Charlesworth & Willis, 2009). Despite its ecological and economic importance, there has been a marked decline in IMC spawning in the Halda River in recent decades (Islam *et al*., 2016; Kibria *et al*., 2022). This study seeks to address the gap in understanding the cumulative effects of environmental and anthropogenic factors on the river's declining ecological health and IMC spawning success. Halda is distinguished as the only natural breeding ground in Bangladesh where IMC eggs are collected directly by spawn fishers, underscoring its ecological importance (Hossain *et al*., 2015). The livelihoods of approximately 1,100 egg collectors and 2,000 fishermen depend directly on the Halda River for their economic survival (Kibria *et al*., 2022; Akhtar *et al*., 2017). Water quality is a crucial factor, with parameters such as temperature, dissolved oxygen (DO), pH, free CO_2, and alkalinity significantly influencing fish growth and reproduction

(Islam *et al.*, 2022; Asaduzzaman *et al.*, 2022; Volkoff & Ronnestad, 2020; Kuparinen *et al.*, 2011; Akther *et al.*, 2024). Unfortunately, the water quality of the Halda River has deteriorated due to both natural and anthropogenic factors. Pollution from various sources, unplanned dam constructions, and sand mining have degraded the water, making it less suitable for fish and reducing fish production (Islam *et al.*, 2016; Arshad-Ul-Alam and Azadi, 2016; Dey *et al.*, 2021). The construction of rubber dams and the withdrawal of water have further compounded these issues, impacting aquatic species and increasing river erosion and salinity intrusion (Jannatul *et al.*, 2015; Raihan *et al.*, 2021). Climate change poses additional threats to the Halda River ecosystem. Altered rainfall patterns, increasing temperatures, and salinity intrusion have been linked to adverse effects on the timing and success of IMC spawning (Hossain *et al.*, 2022). These environmental changes, combined with anthropogenic pressures, are reducing the availability of suitable spawning habitats and exacerbating inbreeding risks, leading to decreased fish populations (Islam *et al.*, 2016). While earlier research has identified several issues impacting the Halda River, there is a lack of comprehensive studies investigating the complex interplay of environmental degradation, anthropogenic pressures, and climate change on IMC spawning. The novelty of this study lies in its integrated approach to understanding these interrelationships. This study aims to identify the primary environmental and anthropogenic factors responsible for the decline in IMC spawning and to provide a framework for understanding how these factors affect the river's ecological health. By evaluating water quality parameters, stakeholder perceptions, and secondary data on egg and fry production, this research seeks to offer insights and management strategies to address the challenges facing the Halda River.

MATERIALS AND METHODS

Study sites

The study was conducted over a one year from December 2020 to November 2021, with intensive observation of breeding activities during the spawning period. Study sites were selected based on the density of spawn fishers and proximity to spawning grounds. The chosen sites included Madunaghat (Madarsha Union), Ramdashat (Madarsha Union), Gorduara (Gorduara Union), and Sattarghat (Mekhol Union) (Figure 1). These sites were ideal for egg collectors and were adjacent to key spawning grounds such as Napiterghat, Ajimerghat, Kagotia, Ankurigona, Gorduara, and Madharimukh (Akhtar *et al.*, 2017).

Sample selection

A total of 150 respondents were selected for data collection, comprising 50 egg collectors, 30 fry rearers, 40 hatchery workers, 10 fisher leaders, 10 fish farmers, and 10 fry buyers. The sample size was determined using the cluster sampling formula outlined by Hahn *et al.* (2009):

n = DEFF × [z2 × p × q)/ e2] where, n = sample size; DEFF = 1; z = 1.96 (95% confidence interval); p= 0.5; q = 0.5; e = 0.10.

The present condition of the selected study area was observed during the spawning period through frequent visits to the site. The collected fertilized egg was brought to the nearest hatchery for hatching. Moreover, during the spawning period, frequent (2 times daily) visits were made to the adjacent hatchery of the selected sites to observe the smooth functioning of egg hatching. The qualitative data were collected predominantly from primary and secondary sources (Figure 2).

Measurement of water quality

During the spawning period, measurements were taken at intervals of seven days to determine the salinity, conductivity, temperature, turbidity, pH, and other significant physicochemical parameters of the water quality under consideration. A Hack multimeter, PHC 101 pH probe, DO probe, amber bottle, beaker, Sachi disk, Multi-parameter with CDC-401 probe, and HACH HQ40d multi-parameter were used to measure and record these physicochemical parameters regularly.

Compilation of the respondent's perception of cause identification

A field survey was carried out using a standard questionnaire during the study period to determine the likely causes (natural, anthropogenic, unanticipated, and environmental) of the decline in carp egg and fry production in the Halda River. Random respondents were interviewed face-to-face using questionnaires to gather data. The questionnaire survey was conducted with 150 respondents in all, including 50 egg collectors, 30 fry rearers, 40 hatchery workers, 10 leaders of fisher groups, 10 fish

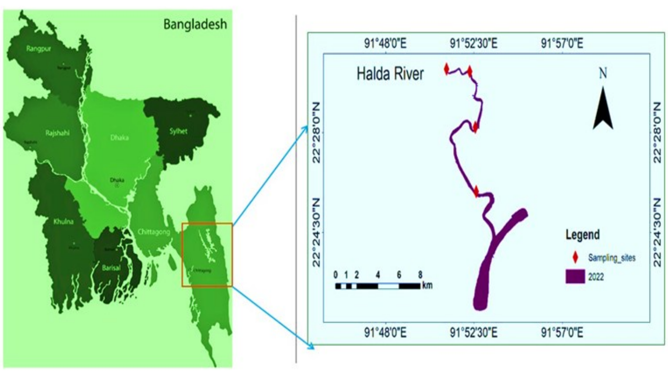

Figure 1. *Map showing the selected study sites of the Halda River.*

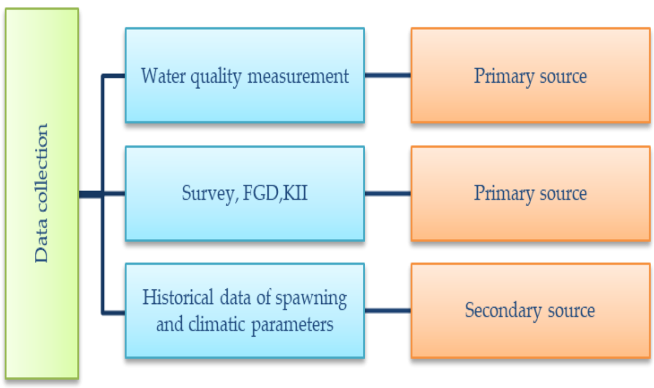

Figure 2. *A framework of the study plan.*

farmers, and 10 fry purchasers. With the assistance of knowledgeable staff members, the questionnaire preparation and the research plan's design were completed. Each participant group had a 20-minute interview during which pertinent responses were gathered. Through answering the questionnaire, information was acquired utilizing both qualitative and quantitative techniques. The purpose of the focus group discussion (FGD) was to get additional precise and condensed information regarding the interview. Data on water quality and egg production were collected directly from the research site. Key informant interviews (KIIs) were conducted with local NGO staff, scientists from BFRI, Upazilla Fisheries Officers (UFOs), Fisheries Extension Officers (FEOs), and other government officials to validate the data on egg and fry production and identify potential risk factors contributing to its decline. Closed-ended questions were employed to categorize participants according to their level of awareness. The most frequently used type of closed-ended question in this study aimed to assess participants' knowledge. Key questions included: a) What is the status of carp spawning performance? b) Has climate change impacted the spawning of carp species in the Halda River? c) What are the effects of human activities on the spawning performance of carp species? d) Denote any unexpected causes that trigger the lower spawning of carp in the Halda River. With the possible answers of spawning status sufficient or not for question 'a'; enlisted the most responsible climatic and man-made factors for declining of carp spawn for questions `b' and `c'; listed down the unexpected causes for lower spawning for question `d'; All the answers to the questions were structured as yes or no, and if yes, then the participants were requested to mention some probable causes. Finally, the data collected information was tabulated and summarized.

Secondary data collection for cross-checking

The HRRL (Halda River Research Laboratory) provided secondary data on the volume (kg) of egg and fry production for the previous ten years. NASA (National Aeronautics and Space Administration) and the Bangladesh Water Development Board's Power Data Access Viewer provided the key components of the spawning temperature and precipitation data for the previous ten years. For more information, secondary data was gathered from many books, newspapers, journals, articles, and other sources.

Data analysis

IBM SPSS Statistics version 22 was used to perform all the statistical analyses for this investigation. We plotted and managed data using Microsoft Excel 2010. After determining that the data were homogeneous and normal, a one-way ANOVA was run to evaluate the average overall effect of the various experimental groups, and the Dancun multiple range test ($P < 0.05$) was then conducted. Simple statistical techniques were also used for processing the tabular and graphical displays.

RESULTS AND DISCUSSION

Water quality parameters for spawning success

The water quality parameters are presented in the Table 1. The highest temperature was found at 30.66±0.56°C, 30.66±0.42°C, Modunaghat, and Ramdashat, respectively, and the lowest was 29.83±0.40°C. In all the locations, the temperature was around 30°C. The lowest DO was observed at 4.85 ± 0.24 ppm in Ramdashat and the highest at 6.10±0.49 ppm in Sattarghat. The pH observed in the study was highest at Sattarghat (6.99±0.07) and lowest at Gorduara (6.86±0.12), respectively. There was no variation, and a suitable level of pH was observed in those four stations. The mean value of the TDS was highest (225.32±109.76 ppm) at the study sites in Modunaghat, where the lowest TDS was found in Gorduara at 102.63±19.56 ppm. Sattarghat showed the lowest value (103.45±13.37 ppm), while the total dissolved solid was found in Randashat at 133.37±42.53 ppm. Karim *et al.* (2019) reported that the water temperature in the Halda River ranged between 28°C and 29°C during the breeding season, which is considered ideal for supporting aquatic life. However, more recent studies have shown an increase in water temperature to 29.83°C–30.66°C, which may be contributing to the decline in Indian Major Carp (IMC) spawning activity. Similarly, Hasan *et al.* (2020) found that while IMCs begin spawning when water temperatures exceed 24°C, the optimal conditions for spawning are within the range of 25°C to 28°C. Temperatures above 30°C negatively affect the success rate of egg release and fertilization, leading to reduced spawning activity, thus corroborating the findings of this study. Sharif *et al.* (2017) highlighted that dissolved oxygen (DO) levels below 5 ppm harm aquatic life, with levels under 2 ppm causing fish mortality. They also reported that the Halda River's water is consistently alkaline, with pH levels between 7.08 and 7.65,

Table 1. Water quality parameters (Mean ± SE) of four sampling sites in Halda River during the spawning period.

Parameters	Site 1 (Modunaghat)	Site 2 (Ramdashat)	Site 3 (Gorduara)	Site 4 (Sattarghat)	Reference value
Temp. (°C)	30.66±0.56^a	30.66±0.42^a	29.83±0.40^a	30.00±0.82^a	25-28 (Hasan *et al.*, 2020)
DO (ppm)	4.92±0.32^a	4.85±0.24^a	5.28±0.27^b	6.10±0.49^b	4-6 (Uddin *et al.*, 2014; Sarker *et al.*, 2015; Hossain and Patra, 2020)
pH	6.96±0.07^a	6.96±0.08^a	6.86±0.12^a	6.99±0.07^a	6.5-8.5 (Uddin *et al.*, 2014)
TDS (ppm)	225.32±109.76^a	133.37±42.53^a	102.63±19.56^a	103.45±13.37^a	<400 (Uddin *et al.*, 2014)
Salinity (ppt)	0.23±0.11^a	0.14±0.04^a	0.10±0.02^a	0.10±0.01^a	0.1-0.3 Rahman *et al.* (2018)
Turbidity (ppm)	203.65±44.82^a	238.82±67.25^a	107.58±23.22^a	143.95±25.61^a	-
Conductivity (µS cm^{-1})	484.10±238.74^a	295.10±95.70^a	224.85±45.51^a	219.85±27.81^a	800-1000 (Sarker *et al.*, 2015)

Table 2. Respondent's perception (%) on natural causes for declining the spawning of IMCs in Halda River.

Parameter	Respondents' categories					
	Egg collectors (n=50)	Fry rearer (n=30)	Hatchery worker (n=40)	Fish farmer (n=10)	Fry buyer (n=10)	Fishers' leader (n=10)
High temperature	90(45)	83(25)	85(34)	80(8)	70(7)	80(8)
Insufficient rainfall	86(43)	73.33(22)	80(33)	80(8)	70(7)	80(8)
Reduced hill water runoff	84(42)	66.66(20)	70(28)	80(8)	70(7)	60(6)
Weather fluctuation	70(35)	60(18)	50(20)	70(7)	60(6)	70(7)
Insufficient water current	60(30)	53.33(16)	60(24)	60(6)	50(5)	50(5)

n= Number of respondents; Figure in parentheses represents the perceived respondents.

noting that minor pH variations do not significantly affect fish habitats. Chapman *et al.* (2016) mentioned that total dissolved solids (TDS) indicate mineral presence, such as nitrites and ammonia, with permissible levels capped at 2000 ppm. The Halda River's salinity levels remain low during the wet season (May to October), typically below 0.5 ppt, due to high freshwater inflow. This supports a freshwater environment essential for fish spawning and ecosystem health. During the study period, the highest salinity was recorded at 0.23±0.11 ppt in Modunaghat, while the lowest values were 0.14±0.04 ppt, 0.10±0.02 ppt and 0.10±0.01 ppt in Ramdashat, Gorduara, and Sattarghat, respectively with no significant differences. Rahman *et al.* (2018) reported average salinity levels of 0.1 to 0.3 ppt indicating minimal saltwater intrusion. In case of turbidity, the results showed that the highest turbidity in the study area was 238.82±67.25 ppm in Ramdashat, and the lowest was 107.58±23.22 ppm in Gorduara site. The highest conductivity recorded was 484.10±238.74 µS cm^{-1} in Modunaghat, while the lowest was 219.85±27.81 µS cm^{-1} in Sattarghat. However, the Halda River's salinity rises due to decreased rainfall during the spawning season, changing its physicochemical characteristics (Ahmed, 2013) and upsetting the aquatic ecosystem that is necessary for IMC spawning. The river's ability to produce eggs has been significantly decreased by the combined effects of rising temperatures and salinity.

Effects of climate change on carp egg and fry production

In the study area, the majority of respondents identified (Table 2) high temperatures (90%), insufficient rainfall (86%), and reduced hill water runoff (84%) as the primary natural factors contributing to the recent decline in egg and fry production. Insufficient water currents (60%) were also considered significant in reducing carp egg production. These natural factors negatively impact the spawning environment of carp species in the Halda River. Despite being mature and prepared to spawn throughout the spawning time, the IMCs' capacity to lay eggs was impeded by these unfavorable conditions, which led to a decrease in the number of fry. Climate change may have a direct impact on the 2021 carp egg and fry production drop as compared to the previous year. The study revealed that the climatic conditions essential for a favorable spawning environment were not met. Kabir *et al.* (2015) observed that reduced rainfall and decreased hill water flow during critical spawning periods lead to increased salinity levels in the river, disrupting the optimal physicochemical conditions for IMC spawning and negatively impacting egg development and hatchling survival.

Analysis of weather data from 2012–2021 revealed a significant drop in precipitation (Figure 3A) in 2021 (148.9 mm) coupled with higher temperature (30.54°C) (Figure 3B) during the spawning season. While water discharge appeared favourable, a reduced water was observed (Figure 3C, D). Although 2016 and 2017 showed higher precipitation, spawning activity remained low, indicating that both insufficient and excessive rainfall may disrupt IMC spawning in the Halda River. These findings suggest that optimal precipitation levels, along with stable hydrological conditions, are critical for successful spawning. Akhtar *et al.* (2017) reported that irregular weather patterns, rising temperatures, uneven rainfall, and reduced water currents make spawning times unpredictable, complicating efforts to protect spawning grounds. Reduced rainfall and groundwater levels have placed pressure on wetlands, reducing fish species and productivity (Kais & Islam, 2019; Aziz *et al.*, 2021).

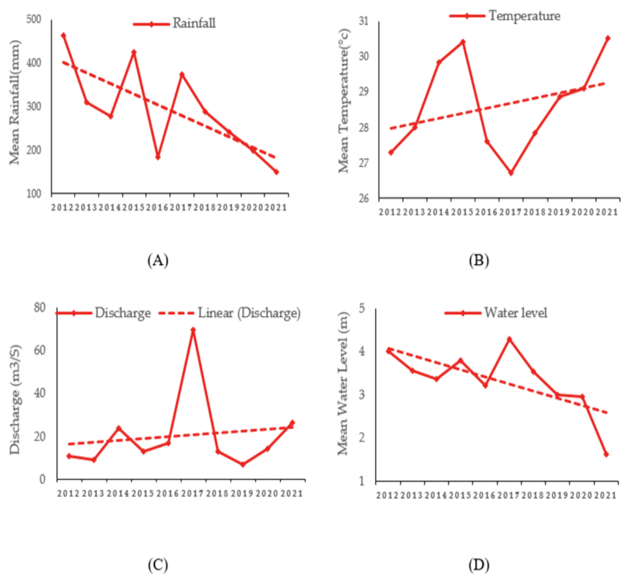

Figure 3. *Graphical representation of the mean Rainfall (A); Temperature (B); Water Discharge (C) and Water Level (D) during the spawning period (March-July) of the last 10 years at Halda River.*

Table 3. Perceptions (%) on anthropogenic causes for the decrease of the IMCs spawning and fry production.

Parameter	Respondents' categories					
	Egg collectors (n=50)	Fry rearer (n=30)	Hatchery worker (n=40)	Fish farmer (n=10)	Fry buyer (n=10)	Fishers' leader (n=10)
Sluice gate	84(42)	70(21)	80(32)	80(8)	80(8)	70(7)
Rubber dam	78(39)	70(21)	75(30)	70(7)	70(7)	60(6)
Pollution	76(38)	73.33(22)	75(30)	70(7)	70(7)	60(6)
Brood fish hunting	50(25)	46.66(14)	55(22)	70(7)	60(6)	70(7)
Cutting of river bend	80(40)	70(21)	75(30)	80(8)	70(7)	60(6)
Sand mining	68(34)	43.33(13)	50(20)	50(5)	50(5)	40(4)
Kumb*fillup	70(35)	56.66(17)	65(26)	70(7)	50(5)	50(5)

n= Number of respondents; **Kumb*- circle type of deeper portion creates by water currents adjacent to oxbow bends; Figure in parentheses represents the perceived respondents.

Table 4. Carp eggs and fry production in nearest study site hatcheries in 2021 spawning period of Halda River.

Name of the Hatchery	Egg amount (kg)	Fry amount (kg)	Successful hatching (%)
Madunaghat Hatchery	770	8.5	1.10
Shahmadari Hatchery	750	7.5	1.00
Machuagona Hatchery	1220	15.0	1.20
IDF Hatchery	600	9.0	1.50

Impact of anthropogenic factors on the decreased number of carp eggs

The decline in carp spawning performance in the Halda River has been significantly influenced by various anthropogenic activities. Respondents identified several key human-induced factors, with the most prominent being sluice gates (84%), river bend alterations (80%), and rubber dams (78%) (Table 3). These factors directly impact the natural flow and hydrodynamics of the river, which are critical for successful carp spawning. Both climate factors, such as temperature and rainfall, and human activities, including pollution, have contributed to the decline in carp spawning (Islam *et al.*, 2015; Akhtar *et al.*, 2017). Illegal brood fish capture, industrial waste, and sand mining have exacerbated the problem, though recent enforcement and monitoring efforts have mitigated some issues (Khatun *et al.*, 2017; Islam *et al.*, 2020). The hydrological conditions of the water body have a significant influence on fish species' spawning (Akther *et al.*, 2023). Sharanika (2020) reported a significant decline in egg and fry production in recent years, with fluctuations driven by water pollution caused by unregulated industrialization, urbanization, and agricultural runoff (Bhuyan *et al.*, 2017; Islam *et al.*, 2020). Human activities such as sand mining, illegal fishing, and the construction of sluice gates have further degraded the Halda River's ecosystem (Saimon *et al.*, 2016). As fewer brood fish release eggs, egg and fry availability has sharply decreased (Hossain *et al.*, 2022; Alam *et al.*, 2022). High pollution levels, especially in Modhunaghat, where DO levels dropped to 0.93 ppm during spawning, underscore the severity of the issue (Bhuyan *et al.*, 2017). Sluice gates, used to control water levels and flow for irrigation or flood control, can disrupt the natural water currents required during the spawning season. Altered water flow reduces the necessary river conditions for egg release and fertilization, as noted by Khan *et al.* (2017) in other studies on riverine fish species. Additionally, rubber dams can block or reduce water flow, further deteriorating the spawning environment by altering water quality and reducing dissolved oxygen levels (Sharif *et al.*, 2017). The loss of these natural spawning habitats further exacerbates the decline in carp reproduction (Kabir *et al.*, 2015). Other factors such as pollution, illegal brood fish capture, sand mining, and the filling of *kumb* (pools or depressions used as spawning grounds) also contribute to habitat degradation. Pollution from agricultural runoff and industrial waste can decrease water quality, increasing toxicity levels that negatively affect egg development and hatchling survival (Florescu *et al.*, 2011). Illegal brood fishing during the spawning season further diminishes the population, reducing the number of viable spawners available each year (Rakib *et al.*, 2021). Sand mining and the filling of kumb destroy key spawning areas, preventing fish from accessing their traditional breeding sites (Hossain *et al.*, 2018).

Unexpected risk factors responsible for the decline in ICM's spawning

The study revealed that, alongside natural and anthropogenic challenges, spawn fishers sometimes face unexpected and devastating events. Respondents identified cyclone Yaas as an unexpected natural disaster that created unfavorable conditions for IMC spawning in the Halda River. Although it was a temporary incident, it occurred during the critical spawning period, just a day before egg release. Data from nearby hatchery showed a significant decline in carp egg and fry production in 2021, with 750 kg of eggs and 7.5 kg of fry at the Shahmadari hatchery, and 1220 kg of eggs and 15 kg of fry at the Machuagona hatchery (Table 4). The highest hatching rate was observed at the IDF hatchery (1.5%), while Shahmadari hatchery had the lowest (1%). The decline in fry production was attributed to technological errors, climatic disruptions, and reliance on river water for egg hatching. Poor management, lack of fresh water, and delayed water supply at Shahmadari further impacted hatching rates. Additionally, increased river salinity and higher temperatures posed significant challenges for spawn fishers. Climate change intensifies these issues, with irregular monsoons and unpredictable rainfall affecting spawning triggers (Hossain & Roy, 2020).

Table 5. The water-related ecosystem services enlisted from previous research studies.

Function	Services	References
Provisioning	The water ecosystem produced food and provided raw materials	Hossain *et al.* (2016)
Regulating	Fights against extreme events for management, climate regulation, water regulation, etc.	Hoque *et al.* (2022)
Supporting	The water environment supports a vast number of biodiversity, protects the biodiversity, and soil formation, retention of the waste management	Ahammad *et al.* (2021)
Culture	Recreational activities, cultural value, tourism, etc.	Smith & Doe (2020)

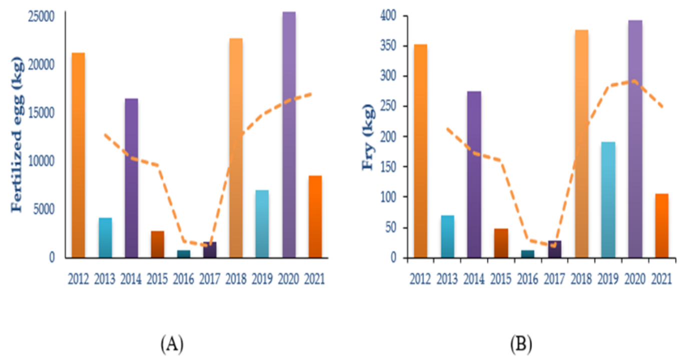

Figure 4. Status of carp's fertilized eggs (A) and fry production (B) moving average trend line of 10 years.

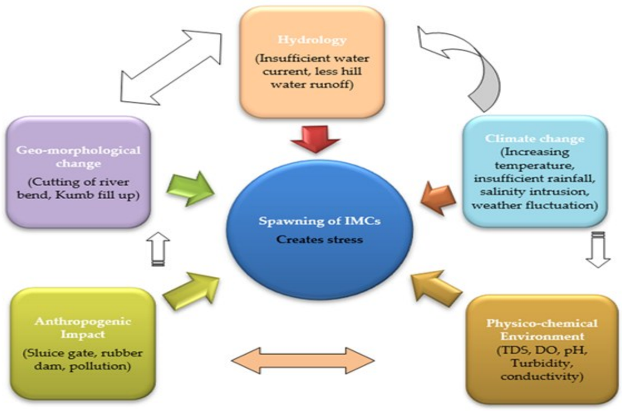

Figure 5. *Conceptual framework showing the key characteristics of all influential factors relating to IMCs spawning in the Halda River.*

Status of carp's eggs and fry production in the Halda River

Over the past decade, carp egg and fry production in the Halda River has fluctuated significantly due to environmental, climatic, and anthropogenic factors. Historically a key natural breeding ground for Indian Major Carps (IMCs) in Bangladesh, the Halda River has experienced a steady decline in production. Recent data from the Halda River Research Laboratory (HRRL) showed that in 2021, only 8,580 kg of eggs and 105.73 kg of fry were collected (Figure 4), representing a 73% and 66% decrease, respectively, compared to the previous year. Over the last 10 years, production has dropped significantly, with egg collection falling below 1,000 kg in certain years, including the lowest production recorded was in 2016. In the early 2010s, egg collection was robust, with 14,000 kg recorded in 2012 (Hossain *et al.*, 2013), and by 2018, production had plummeted to just 2,400 kg (Ahmed & Wahab, 2020). Production also varied, with low outputs in 2015-2017 and a slight improvement in 2018-2020. Conservation efforts, including stricter fishing regulations and sand mining restrictions, led to a slight recovery in 2019, with egg collection reaching 5,000 kg (Rahman *et al.*, 2020). Over the past decade, the production of carp eggs and fry in the Halda River has experienced significant fluctuations, largely due to environmental and anthropogenic pressures.

The factors influencing Indian major carps (IMCs) spawning in the Halda River are illustrated using a conceptual framework (Figure 5) that highlights the relationships between them. IMC spawning and river hydrology are directly disrupted by climate change, whereas the physicochemical environment is less affected. Physicochemical, geomorphological, and hydrological conditions are moderately impacted by anthropogenic activities, and spawning is severely hindered. Hydrology is adversely affected by geomorphological changes as well, which together create stress that prevents successful spawning (Figure 5). In addition to providing provisioning, regulating, supporting, and cultural services, the water-related ecosystem boosts natural productivity and is essential for biodiversity. Any disruption in one ecosystem service has the potential to affect the entire ecosystem (Table 5).

Conclusion

This study highlights a significant loss in the Halda River's spawning success for Indian major carps (IMCs), with egg production decreasing by 66% to 8,580 kg and fry yield reducing by 73.3% to 105.73 kg in 2021 compared to 2020. In spite of human-induced causes like pollution, cutting river bends, rubber dams, and abandoned sluice gates, spawning habitats have been substantially deteriorated by climatic stresses including rising temperatures, reduced rainfall, decreased hill water runoff, and salt intrusion. Anthropogenic activities, including pollution (76%), river bend cutting (80%), rubber dams (78%), and abandoned sluice gates (84%), have further degraded these critical habitats. These findings emphasize the urgent need for targeted conservation strategies to minimize human-induced disturbances, restore natural river dynamics, ecosystem-based interventions, and enhance the resilience of IMC spawning habitats.

DECLARATIONS

Author contribution statement

Conceptualization: K.R.A. and N.C.R.; Methodology: K.R. A.; Software and validation: K.R.A., N.C.R. and A.A.A.; Formal analysis and investigation: K.R.A.; Resources: K.R.A.; Data curation: K.R.A. and N.C.R.; Writing—original draft preparation: M.M.K., M.A.H., and N.C.R.; Writing—review and editing: N.C.R.; Visualization: N.C.R..; Supervision: N.C.R..; Project administration: N.C.R.; Funding acquisition: N.C.R. and K.R.A.; All authors have read and agreed to the published version of the manuscript.

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