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Original article

Reproductive biology of *Heteropneustes fossilis* in a wetland ecosystem (Gajner *Beel*, Bangladesh) in relation to eco-climatic factors: Suggesting a sustainable policy for aquaculture, management and conservation

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ABSTRACT

The stinging catfish, *Heteropneustes fossilis* (Bloch, 1974) is a commercially important fish species in Asia. This is an important food fish as is enriched with high amounts of protein, iron and calcium. The current research demonstrates the population structure, size at sexual maturity, spawning- and peak-spawning season and fecundity of *H. fossilis* in an important wetland ecosystem - Gajner *Beel* in northwestern Bangladesh with an aim of its sustainable conservation through induced breeding and aquaculture practices. A total of 426 stinging catfish captured from the Gajner *Beel* through monthly sampling from January to December 2019 used in the study. Total length (TL), standard length (SL) and body weight (BW) of individual fishes were measured. The size ranges were with 6.70–24.10 cm TL, 1.37–83.94 g BW. Gonads were removed carefully through ventral dissection and weighted. L_m was 14.02, 13.5, 13.0 and 15.0 cm based on maximum length (L_{max}), TL *vs.* GSI (%), TL *vs.* SL and logistic model, respectively. Monthly variations of GSI and maturation stages were confirmed in April to August as spawning season and June as peak spawning month. Fulton's condition factor (K_F) was found to be with significant relations with GSI values. Fecundity was 1,730 to 23,870 and significantly correlated with both TL and BW. Temperature has been increasing 0.029 °C/year with the falling of rainfall at 2.96 mm/year in the study area. Environmental factors -Temperature, rainfall, dissolved oxygen and pH were found to be significantly correlated with GSI. We found the optimal range of temperature (29–31 °C), rainfall (350–380 mm), dissolved oxygen (5.0–6.0 mg/l) and pH (7.1–7.5) for spawning of *H. fossilis*. The paper recommended the policy guidelines to pave the ways of the aquaculture, conservation and management of *H. fossilis* in the changing eco-climatic events through specific management measures.

1. Introduction

The Order Siluriformes (catfish) comprises 4,100 species, which constitute 6.3% of all vertebrate species and 12% of all fish species. Catfish have long been playing key role in biological research, as they are similar to a common fishery parent than most bony fish (infraclass Teleostei) because of their phylogenetic position. Nutritionally, catfish are well-known as a valuable source of dietary protein worldwide (Liu et al., 2016). The stinging catfish *Heteropneutes fossilis* (Bloch, 1794), under the Family Heteropneustidae is generally known as the 'Shingi or Singhee' among Bengali speaking people in Bangladesh and India and diaspora living in other parts of the world (Rahman et al., 2019). The benthopelagic catfish is widely distributed in Bangladesh, India, Laos, Myanmar, Nepal, Sri Lanka, and Thailand (Talwar and Jhingran, 1991). It inhabits mainly in slow and shallow water bodies - ponds, ditches, swamps, marshlands, and sometimes in muddy rivers. As it provides large concentrations of protein, iron (226 mg/100 g) and calcium the fish is dubbed as an essential food fish (Saha and Guha, 1939) and occupy high price in the markets (Alok et al., 1993). IUCN Bangladesh (2015) and IUCN (2000) declared the fish as least concern (LC) in Bangladesh and the world, respectively.

Fruitful fisheries management largely depends on exact assessment of biological parameters, such as reproduction, growth and

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assessment of stock (Tracey et al., 2007). Understanding of reproductive biology of fish species is vital and a prerequisite for conservation and relevant management approaches (Brewer et al., 2008; Grandcourt et al., 2009; Muchlisin et al., 2010). Besides, conscientious evaluations of reproductive behavior unearth dynamic causes that may influence survival in addition to recruitment of different fish species (Khatun et al., 2019). Fish population replenishment as well as individual potency is mostly dependent on fruitful reproduction (Hossain et al., 2017a). Subsequently, the knowledge of gonadosomatic index, maturation size and spawning period are considered as a key element for the biological researches in fishes (Hossain et al., 2012).

L_m of fish is important in exploring the causes of variations in the length of maturation (Templeman, 1987). In addition, maturation size of fishes is broadly used as a sign of minimum-allowable capture size (Lucifora et al., 1999; Hasan et al., 2021). Estimation of spawning/breeding season in fish is essential mainly for the conservation of adult or mature individuals from heavy fishing pressure (Templeman, 1987; Mawa et al., 2021). The condition factor indicates the level of wellness of the fish in their natural environment. It is an essential measure of different ecological and biological variables such as the degree of fitness, the production of gonads and the suitability of the atmosphere with respect to the feeding state (Mac Gregoer, 1959).

Fecundity is a vital element of fish biology that must be recognized to understand variations in population levels and to make attempts to raise the high amount of harvest capability. (Akter et al., 2007). The fecundity referred the total number of eggs that is produced by a female during the usual life-span. The number of ripening eggs in female ovaries before spawning can also be recognized (Shrivastava, 1999; Hossain et al., 2021). It must be known to assess the reproductive potentialities of a fish stock (Lagler, 1956) and to understand of reproductive strategy (Nazari et al., 2003).

The reproductive cycle is an equitable mechanism related to the environmentally regulated routine of organisms living in different aquatic environments. Therefore, the normal breeding mechanism of the fish community may be influenced by some unfavorable environmental factors and may eventually inhibit the process of recruiting into the stock by spawning and hampering the migration process. Environmental factors (e.g. rainfall, temperature) and changes in water hydrological parameters (e.g. Do, pH, and alkalinity) have effects on fishes especially in their ecology and growth (Lappalainen et al., 2008; Britton et al., 2013; Hossain et al., 2021). In addition, temperature is a fundamental physical regulator in fish life, and its influence is strongly embodied in the management of all reproductive processes, from gamete growth and maturation, ovulation and permeation, breeding, embryonic development and laying eggs, to larval and juvenile growth and survival (Pankhurst and Munday, 2011). Water temperature is also known as a major element of fish growth i.e. the growth rate of aquatic organism is reduced with the decrease of water temperature (Blanck and Lamouroux, 2007; Lappalainen et al., 2008).

Fisheries management is sometimes regarded as a reaction to 'common failure,' in which the lack of exclusive property rights means that fish are overfished and resources and labor are wasted (Wilson and McCay, 2001). Aquaculture, or water farming, is the rearing, breeding, and cultivation of fish, shellfish, and aquatic plants. It has been considered as an effective and environmental friendly form of production of food and commercial goods, ensures ecosystem sustainability and restores threatened or endangered organisms (NOAA, 2020).

H. fossilis has immense aquaculture potential and may easily be farmed in ponds and shallow ditches. The culture of this fish is yet to flourish in Bangladesh owing to a lack of effective culture technologies (Roy et al., 2019). Most of the *Beels* are dried out during half of pre-monsoon and post monsoon period due to the increasing temperature and decreasing rainfall. In addition, lacks of good

Table 1
Available works on different aspects of *Heteropneustes fossilis* world wide.

Aspects	Water body/Country	References
Biometrics relationships		
Length-weight relationships	Ganga River	Khan et al. (2012)
length-weight relationship and conditions	Ramsar site, Assam, India	Das et al. (2015)
length-length, length-weight relationship and conditions	Nageshwari, Banglaesh	Ferdaushy and Alam (2015)
Length-weight relationships	Gajner *beel* floodplain	Hossain et al. (2017b)
length-weight relationship and conditions	Indus River, Pakistan	Muhammad et al. (2017)
length-weight relationship and conditions	Atrai and Brahmaputra Rivers	Islam et al. (2017)
Morphometrics and meristics	Gajner *Beel*	Rahman et al. (2019)
Reproduction		
Spawning season	Bangladesh	Shafi and Quddus (1982)
Induced spawning of the Indian catfish	India	Joy and Tharakan (1999)
Fisheries of Bangladesh		Saud et al. (2015)
Fecundity of the freshwater catfishes	India	Bhatt et al. (1977)
Freshwater fishes of Bangladesh	Bangladesh	Rahman (1989)
Fisheries of Bangladesh	Bangladesh	Shafi and Quddus (2001)
Gonado-somatic index and fecundity	Brahmaputra River, Assam, India	Saud et al. (2015)
Growth		
Impact of eco-hydrological factor on growth	*Gajner beel*	Hasan et al. (2020)
Age and Growth	Tangail, River Brahmaputra	De Graaf (2003)
Population parameters	Medi beel, Netrokona District	Mustafa and De Graaf (2008)
Aquaculture and Hatchery		
Water quality, growth and production performance	Bangladesh	Roy et al. (2019)
Effect of stocking density on growth, survival and production	Bangladesh	Monir and Rahman (2015)
Induced Breeding	Bangladesh	Rahman et al. (2013)
Induced spawning of catfish	India	Alok et al. (1993)
Biochemical impacts of salinity	Bangladesh	Ahmmed et al. (2017)
Culture potentials	Bangladesh	Rahman et al. (2014)
Effect of feeding frequency on surfacing activity	India	Marian et al. (1982)
Effects of dietary protein levels	India	Siddiqui and Khan (2009)
Comparative growth performance assessment	Bangladesh	Nushy et al. (2020)
Impacts of different diets on growth	Bangladesh	Ahmmed et al. (2016)
Optimum ration level for better growth	India	Khan and Abidi (2010)
Seed Production an Urgent Need	India	Haniffa et al. (2017)

quality seed is also an obstacle in the way of developing aquaculture of *H. fossilis*. For the profitable and sustainable fish farming, seed is very important. Fish seeds (fertilized eggs, spawns, fry and fingerlings) collected from open water bodies are preferred by the fish farmers over the seed produced in the hatchery.

There are a few studies conducted on *H. fossilis* reproduction (Table 1) including the study on reproductive biology (Talwar and Jhingran, 1991; Joy and Tharakan, 1999) and on fecundity (Bhatt et al., 1977). However to date no study explored the reproductive biology and its relation with eco-climatic factors for this important fish species. The present study was the first attempt that covered the key aspects of reproduction, including length at first sexual maturity and spawning seasons, and fecundity using various models considering the changes in climatic factors as well as the aquaculture, conservation and management aspects of *H. fossilis* in the wetland ecosystem of Bangladesh.

2. Materials and methods

2.1. Sampling site and fish measurement

Monthly samplings were done from the Gajner *Beel* wetland ecosystems, northwestern Bangladesh during the January to December 2019 (Fig. 1). Cast net (1.5–2.5 cm, day time: 8.30 to 9.30 am) was used to collect the samples with the help of local fishers. Specimens were immediately preserved in ice and transported to the laboratory and preserved in a deep freezer until further analysis. Before taking measurements, each specimen was dipped with water, washed, and taken on a tray. Then lengths were measured (TL, and SL, to closest 0.1 cm) by a measuring board and total weight was taken (BW, to nearest 0.01 g) by an electronic balance. Sex identification was done through observing gonads under a microscope and by evaluating the meristic and morphometric characters of fishes. Length frequency distribution for *H. fossilis* was calculated individually with 1 cm intermissions of TL.

2.2. Size at sexual maturity (L_m)

The L_m was estimated using several functions (i) Based on maximum length, log (L_m) = -0.1189 + 0.9157* log (L_{max}), (Binohlan and Froese, 2009). (ii) The relationship of TL *vs.* GSI, GSI (%) = (GW/BW) × 100. (Nikolsky, 1963) (iii) The alteration point of TL value from TL-SL statistics helped to estimate L_m using the equation of Huxley (1932): y = *a* + *b*x. A discrete linear regression was calculated for each subset of the data and arranged at 0.5 cm intervals of the break point above the total size frequency of females. The calculations were repeated several times. From the minimum residual sum of squares (RSS), the change was identified in the subsequent two subsets of data (Pankhurst and Munday, 2011; Ahamed and Ohtomi, 2014). Furthermore, the growth type was identified by regression analysis from untransformed TL-SL data. For this length-length relationship, significant discrepancy of *b* values from the hypothetical isometric value (*b* = 1) of growth was either positively (*b* > 1) or negatively allometric (*b* < 1) (Hartnoll, 1982). ANCOVA (analysis of covariance) was used to check for significant deviation in slopes and intercepts between the two subsets of data (Zar, 1984). (iv) A logistic curve was fitted to the maturity information by distributing the percentage of mature individuals (PMI) against TL class. PMI = 100/ [1 + exp{-*f* (TLm - TL50)}], where *f* refers to growth coefficient and TL_m is the midpoint of every TL class (King, 2007). PMI never exceeds 100%, even though the biggest TL classes of all mature individuals in a population are simultaneously in a reproductive cycle. Thus, the data were adjusted to overcome an unnecessarily high estimation of TL_{50} according to the method of King (2007).

2.3. Spawning season

Spawning season was estimated using two methods (i) monthly changes in gonadosomatic Index (GSI) (Khatun et al., 2019) and (ii) seasonal progression of gonads (maturation stages of gonad) (Zhang et al., 2009). Gross physical (morphological) analysis of the ovary reported macroscopic determination of gonad maturity and seasonal progression of the gonad. Depending on the macroscopic features, the maturation stage was defined by the opacity of the gonads, the durability and vascularization and the overall coloring of the gonads (Shinkafi et al., 2011; Nath, 2013).

2.4. Condition and prey-predatory status

Fulton's condition factor (Fulton, 1904) was estimated as a percentage, i.e., (K_F) = 100*(W/L^3). Relative weight (W_R) was

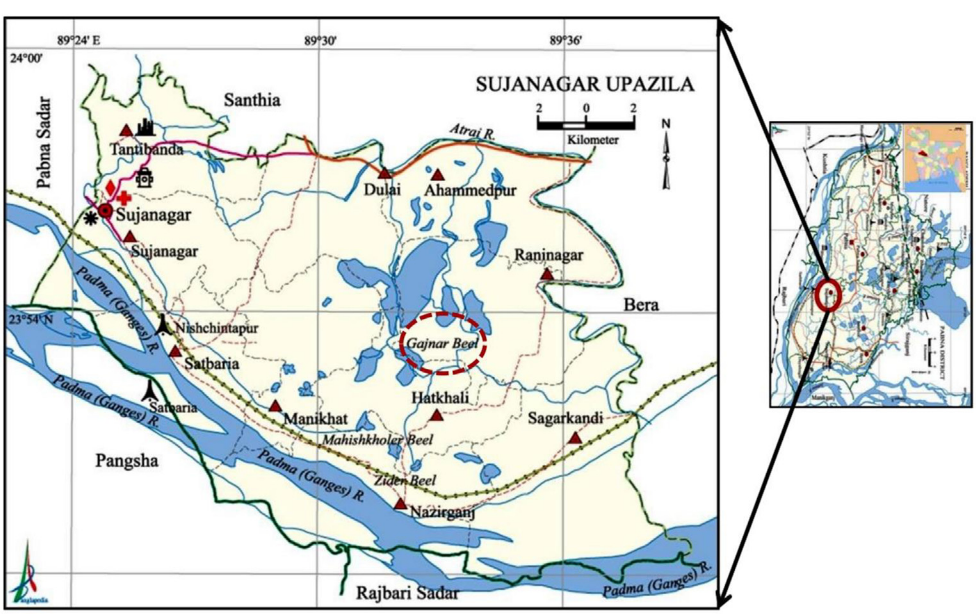

Fig. 1. Sampling sites in a wetland ecosystem (Gajner *Beel*) (indicated by red circle), northwestern Bangladesh.

considered through the formula of Froese (2006): $W_R = (W/W_S) \times 100$, $W_S = a^*L^b$

2.5. Fecundity

According to Murua et al. (2003) total fecundity (F_T) was estimated by gravimetric method. The relationships within F_T, TL and BW were done by, $F_T = m \times (TL)^n$ (non-linear) and $F_T = m + n \times (BW)$ (linear regression).

2.6. Eco-climatic factors

Hydrological data were collected in every month from sampling station by HACH (HQ_{40d}) digital multi-meter parameter. Monthly dissolved oxygen (mg/l), temperature (°C), pH, total dissolved solids (TDS) mg/l and total alkalinity (mg/l) were assessed. A specific sampling time (9:00–11:00 am) was maintained. Climatological data (rainfall and air temperature) were obtained from the meteorological station of Dhaka, Bangladesh.

2.7. Statistical analyses

All statistical studies were performed by Microsoft® Excel, past 4.03 and GraphPad Prism 6.5 software. Normality of data was confirmed by Shapiro-wilk test. The non-parametric Spearman-rank test examined the relationships between (a) eco-climatic information and GSI and (b) condition factors with GSI at a 5% ($p < 0.05$) significance level. The correlation analysis helped to discern the essential environmental features that induced egg maturity and spawning period.

3. Results

3.1. Population structure

From a total of 845*H. fossilis* individuals, 426 female specimens were analyzed. The total length (TL) of the analyzed female fishes ranged between 6.70 and 24.10 cm TL and body weight (BW) ranged between 1.37 and 83.94 g. Weight of gonad was 0.01–25.90 g. Table 2 represented minimum, maximum, mean and 95% CL of TL, BW, and GW. Length-frequency distribution of *H. fossilis* is shown in Fig. 2.

3.2. Sexual maturity

The calculated L_m of *H. fossilis* was 14.02 cm (95% CL = 10.99–17.84 cm) in TL based on maximum length. We also calculated the size at first sexual maturity (L_m) of *H. fossilis* from different worldwide water-bodies based on maximum length which was shown in Table 3. On TL *vs.* GSI relationship, we found the lowest and highest values of gonadal weight studied of the *H. fossilis* were 0.01 g and 25.90 g. The GSI was smaller than 13.50 cm TL was low (<8.80%). The GSI (>8.80%) around 13.50 cm in TL rose sharply for maximum of the female of *H. fossilis*. Therefore, L_m may consider being started from 13.50 cm in TL for *H. fossilis* in the Gajner *Beel*, northwestern Bangladesh. The relationship between TL *vs.* GSI of *H. fossilis* are given in Fig. 3. Spearman rank correlation test revealed significant correlation between TL *vs.* GSI ($r_s = 0.1172$; $p = 0.0155$) indicating that GSI was dependent on body size. Through regression analysis at 1.0 cm intervals of total size range of females, a break point was found with an individual TL value, depending on the lowest total RSS value and comparative growth of TL-SL of *H. fossilis* as distributed into two phases (Table 4). The comparative growth rate of SL was estimated as 13.0 cm TL (Fig. 3). SL rose more promptly than TL after this size and indicated a negative allometric growth pattern (Table 4). ANCOVA showed significant difference in slopes ($p = 0.01$) above by below the alteration point for the observed regression (Table 5). In addition, the logistic equation of mature females for every length class (TL) group was expressed the relations between TL and the mature individuals' percentage values (Fig. 3). We found that the smallest size of mature female was 12.0 cm and a TL of 15.0 cm corresponded to 50% of sexually mature *H. fossilis* females in Gajner *Beel*. Based on above four models, range of L_m was 13.50 to 15.00 cm of *H. fossilis*.

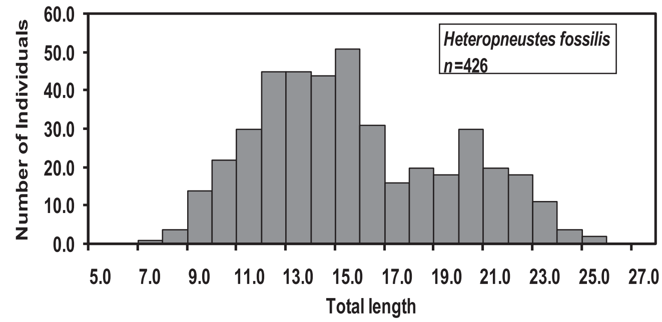

Fig. 2. Length-frequency distributions of female *Heteropneustes fossilis* in the Gajner *Beel*, NW Bangladesh.

3.3. Spawning season

Monthly variations in GSI values are represented in Fig. 4. The ovary started to mature in March and continued until August. The highest GSI values were observed in April to August to define the full reproductive period of *H. fossilis*. In addition the highest GSI values were observed in the June that defines the peak season for spawning of *H. fossilis*.

Five maturity phases were identified from macroscopic investigation (Table 6). Temporal variation in gameto genic patterns of females has showed that the developed condition of gonads (Mature) was found in every month. The highest percentage of mature gonads was observed in June and the lowest was in November. Based on macroscopic features, fishes with gonads with mature stages were considered as spawning and peak spawning season of fishes (Fig. 4).

Table 2
Descriptive statistics on the lengths (cm), body weight (g) and gonad weight (g) measurements of *Heteropneustes fossilis* (Bloch, 1794) in the Gajner *Beel* of northwestern Bangladesh during January -December 2019.

Characters	*n*	Min	Max	Mean ± SD	95 %CI
Total length TL (cm)		6.70	24.10	14.68 ± 3.88	14.31 – 15.05
Standard length SL (cm)	426	6.00	21.80	13.18 ± 3.57	12.84 – 13.52
Body weight BW (g)		1.37	83.94	20.87 ± 17.50	19.20 – 22.54
Gonad weight GW (g)		0.01	25.90	1.16 ± 3.09	0.87 – 1.46

n, sample size; Min, minimum; Max, maximum, SD, standard deviation; CI, confidence intervals.

Table 3
The calculated size at first sexual maturity (L_m) of *Heteropneustes fossilis* (Bloch, 1794) from worldwide different water-bodies based on maximum length.

Water body	Max TL (cm)	L_m	95% CI of L_m	References
Ganges River, India	31.00	17.65	13.70 –22.64	Khan et al. (2012)
Deepar *Beel*, Assam, India	19.10	11.33	8.96 –14.31	Das et al. (2015)
Nageshwari, Bangladesh	15.50	9.36	7.47 –11.75	Ferdaushy and Alam (2015)
Gajner *Beel*, Bangladesh	16.50	9.91	7.89–12.46	Hossain et al. (2017b)
Indus River, Pakistan	13.00	7.96	6.40 –9.94	Muhammad et al. (2017)
Atrai and Brahmaputra Rivers	13.71	8.36	6.71–10.46	Islam et al. (2017)
Gajner *Beel*, Bangladesh	26.80	15.45	12.06–19.72	Rahman et al. (2019)
Gajner *Beel*, Bangladesh	**24.10**	**14.02**	**10.99–17.84**	**Present Study**

TL, Total length; L_m, Size at first sexual maturity; CI, confidence intervals.

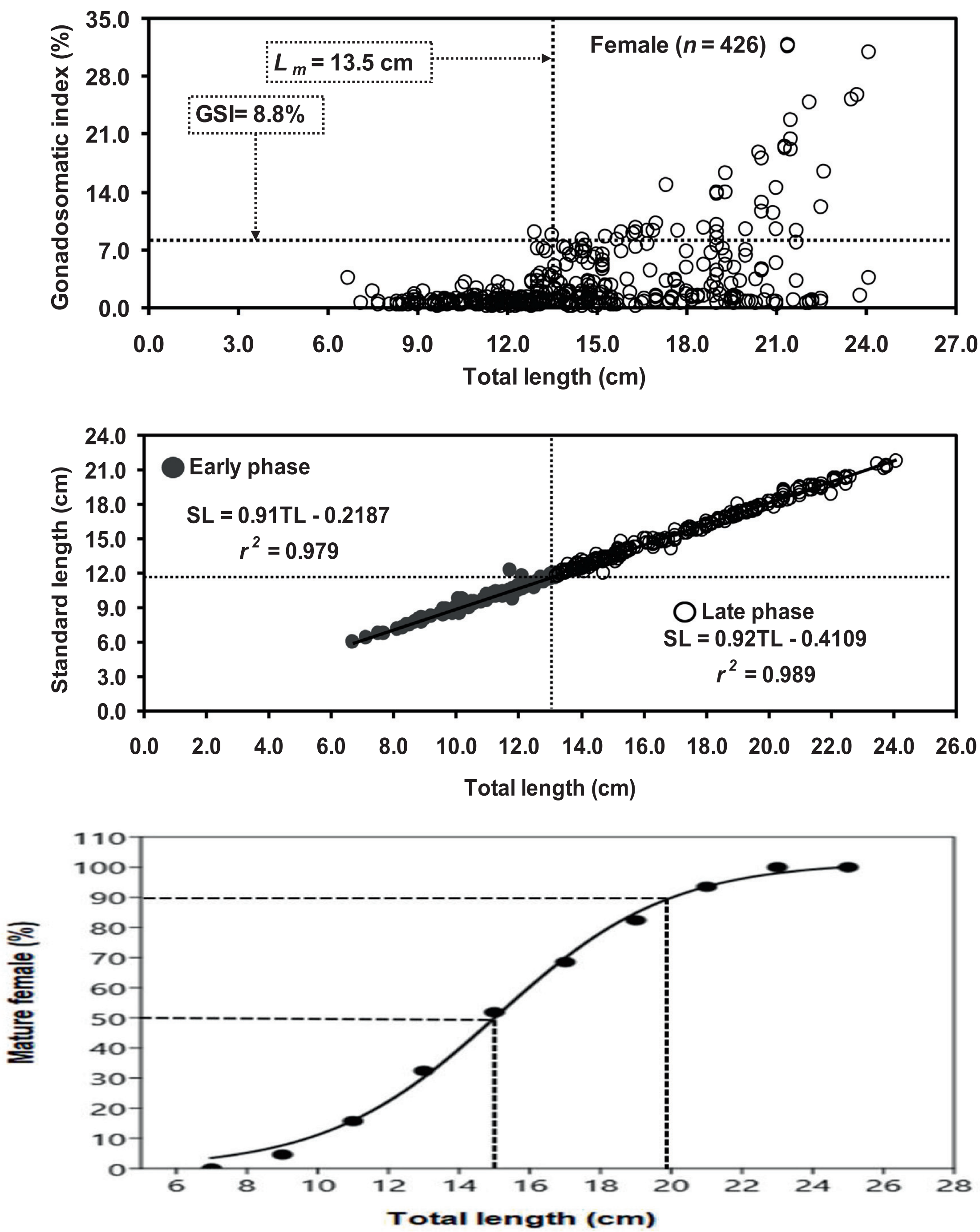

Fig. 3. (i) Relationship between gonadosomatic index (GSI) *vs.* total length (TL) (ii) total length *vs.*standard length and (iii) total length (TL) *vs.* adjusted percentage of *Heteropneustes fossilis* in the Gajner *Beel*, NW Bangladesh.

Table 4
Estimated slope and intercept of linear equation representing the relationship between total length and standard length of female *Heteropneustes fossilis* in the Gajner *Beel*, Bangladesh and RSS in different sets of two phases.

Break pointTL (cm)	Early phase				Late phase				Total RSS
	Slope	Intercept	*n*	RSS	Slope	Intercept	*n*	RSS	
7.0	0.69	1.4245	5	0.020	0.92	−0.3184	421	24.379	24.399
8.0	0.89	−0.0089	19	0.191	0.92	−0.3278	407	24.226	24.417
9.0	0.89	−0.0087	41	0.767	0.92	−0.3420	385	23.613	24.380
10.0	0.88	0.0157	71	0.898	0.92	−0.3403	355	23.469	24.367
11.0	0.90	0.1621	116	5.394	0.92	−0.3724	310	18.976	24.370
12.0	0.89	−0.0600	160	7.170	0.91	−0.3151	265	17.103	24.273
13.0	**0.91**	**−0.2373**	**204**	**19.240**	**0.92**	**−0.3876**	**221**	**4.645**	**23.885**
14.0	0.91	−0.2190	256	11.900	0.92	−0.3548	170	12.495	24.395
15.0	0.92	−0.2678	287	14.597	0.93	−0.4620	139	9.818	24.415
16.0	0.91	−0.2343	303	16.999	0.92	−0.4006	123	7.383	24.382
17.0	0.91	−0.2216	323	17.708	0.91	−0.1385	103	6.578	24.286
18.0	0.91	−0.2318	341	18.110	0.89	0.2007	85	6.060	24.170
19.0	0.91	−0.2622	371	8.655	0.84	1.3603	55	15.754	24.409
20.0	0.92	−0.3204	390	21.632	0.81	2.0120	35	2.489	24.121
21.0	0.92	−0.3492	409	22.699	0.91	−0.3122	17	1.514	24.213
22.0	0.92	−0.3252	420	24.129	0.83	1.7024	6	0.245	24.374

n, Number of individuals; TL, Total length; RSS, Residual sum of square; SL, Standard length.

Table 5
Allometric coefficients measured as slope for linear regressions (by least square estimate, with log-transformed data) between TL and SL of *Heteropneustes fossilis.*

Relationship		*n*	Allometric coefficient		r^2	Significance level
			b	95 %CL of *b*		
TL *vs.* SL	Early phase	179	0.91**	0.88–0.92	0.979	$p = 0.01$
	Late phase	247	0.92**	0.91–0.93	0.989	

** Allometric coefficient significantly ($p = 0.05$) different from 1.0, TL, Total length, SL, Standard length; *n*, Sample size; *b*, Slopes; 95% CI, Confidence interval, r^2, Coefficient of determination.

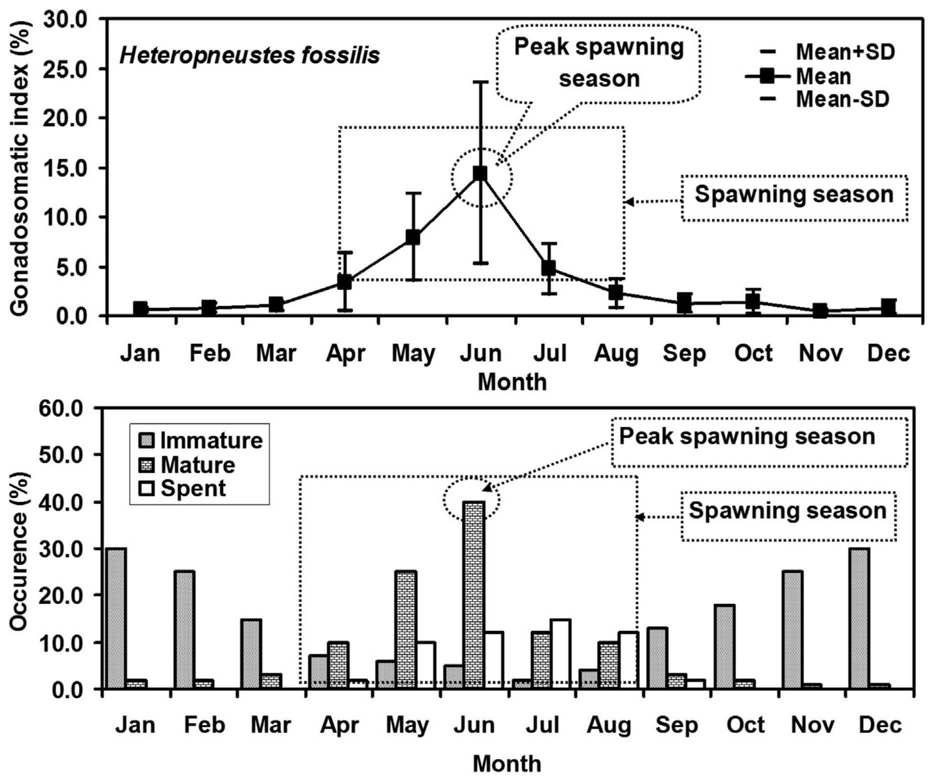

Fig. 4. Monthly variations of gonadosomatic index (GSI) and maturation stage based on colour with maximum and minimum values of female *Heteropneustes fossilis* in the Gajner *Beel*, NW Bangladesh.

Table 6
Macroscopic and description of gonad maturation stages of *Heteropneustes fossilis* in the Gajner *Beel*, northwestern Bangladesh.

Stages	Brief description of gonad
Stage 1: Immature	Ovary cord like, ova invisible to the necked eye, thick membrane.
Stage 2: Maturing	Greenish, more than two and half quarter of body cavity, opaque ova, granular appearance, lobular.
Stage 3: Mature	Green, large occupies all the body cavity, delicate ovary membrane. Ova flow out with gentle pressure.
Stage 4: Ripe	Deep green to blackish, large occupies all the body cavity, delicate ovary membrane. Ova flow out with gentle pressure.
Stage 5: Spent	Flaccid empty sac, reddish bloody with many tiny opaque green residual ova.

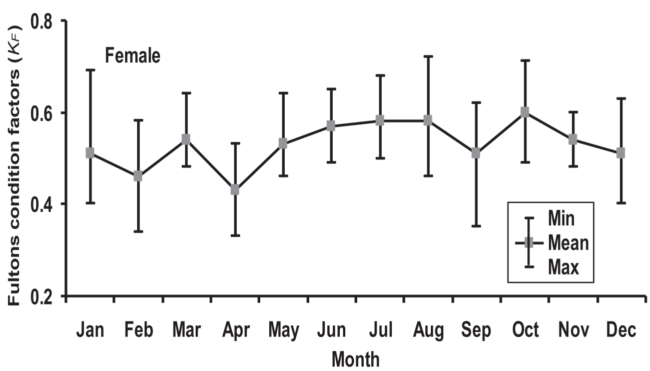

Fig. 5. Monthly variations of Fulton's condition factor (K_F) of female *Heteropneustes fossilis* in the Gajner *Beel*, NW Bangladesh.

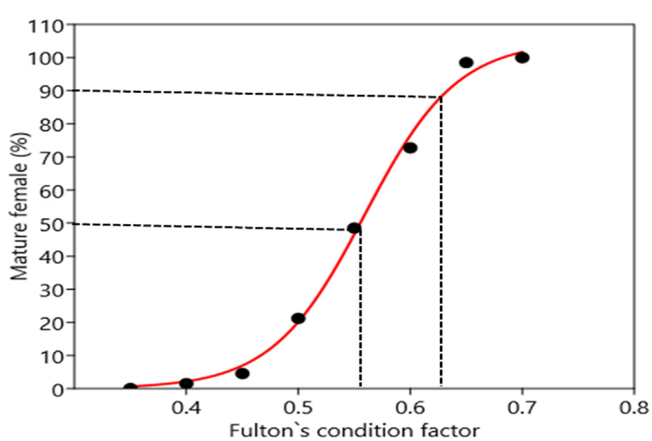

Fig. 6. Adjusted percentage of mature females of *Heteropneustes fossilis* versus condition factor showing the logistic curve fitted to the data.

3.4. Condition factors

The lowermost and uppermost K_F values for females were recorded in April (0.33) and August (0.72), respectively, with an average 0.53 ± 0.07 (Fig. 5). Conferring to Spearman rank test, K_F and TL were significantly correlated for female *H. fossilis* (r_s = 0.2116; p < 0.0001). Further, K_F revealed significant correlation with GSI values (r_s = 0.2495; < 0.0001). Half of the female *H. fossilis* spawned when K_F was 0.55 (Fig. 6). The calculated lowest value of W_R for females was 71.44 (Mean ± SD, 101.35 ± 11.05) in September and the highest was 130.51 (101.11 ± 8.6) in January (Fig. 7). Wilkoxon sign ranked test showed significant differences from 100 for females (p = 0.0122).

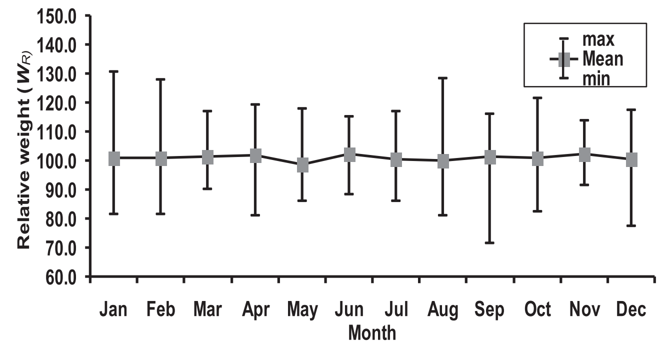

Fig. 7. Monthly variations of relative weight (W_R) of female *Heteropneustes fossilis* in the Gajner *Beel*, NW Bangladesh.

3.5. Fecundity

The mean total fecundity was 11897.78 ± 5027.28 and ranged between 5942 and 49852. Significant correlation was observed between TL and F_T (r_s = 0.967 and p < 0.0001) and between *BW* and F_T (r_s = 0.923 and p < 0.0001). Significant linear relationships were also found for natural log (ln) transferred TL *vs.* F_T (r_s = 0.967 and p < 0.0001) and BW *vs.* F_T (r_s = 0.965 and p < 0.0001). The relationships were shown in Fig. 8.

3.6. Eco-climatic factors

In our study, several environmental parameters were inspected for their influences on gonadal development and spawning of *H. fossilis*. Temperature, total alkalinity, pH and dissolved oxygen were found to be correlated with GSI (Table 7). The relationships between GSI and water quality factors are shown in Figs. 9 and 10.

The optimal hydrological and physicochemical factors for the spawning of *H. fossilis* as observed in the current study are – temperature – 29 to 31 °C, rainfall – 350 to 380 mm, dissolve oxygen – 5 to 6 mg/l and pH – 7.1 to 7.5 (Fig. 11). A lengthy time series data over five decades (1971 to 2019) on air temperature and rainfall were evaluated to assess its changing temporal pattern. In the study area, annual air temperature revealed a rising trend of 0.029 °C/year, with the coefficient of determination value (r^2 = 0.371) whereas the annual average rainfall indicated a dropping trend of 2.98 mm/year (r^2 = 0.045) Fig. 12).

3.7. Seed production and farming for H. Fossilis were reviewed from the existing literatures

The seeds of *H. fossilis* should be collected after two to three months of peak spawning season. Based on SGR (%), survival (%) and production, the maximum stocking density of *H. fossilis* in the culture systems should not exceed 125,000/ha for monoculture and 24,000/ha for polyculture with Indian major carp and other farmed fishes (Table 8). The feeding rates and feeding frequency should be 12–5% (from nursery phase to grow-out, rate gradually decreases as the individual weight increases) and twice/day, respectively, to optimize the production and cost of production for the species. Dietary protein should be 40% and optimum ration level should remain 5% BW day^{-1} (Table 8). The suitable range of temperature was 27.4–29.8 °C, pH 6.8–7.8, dissolved oxygen 6.8 to 8.6 mg/l, ammonia (NH3) < 0.1 mg/l for good aquaculture.

A healthy broods produced a healthy offspring. In the hatchery good quality of broods are insufficient so we can easily collect the broods from the spawning season. It's also help to avoid the cross breeding in hatchery. According to survey results all researchers are agreed that ovaprim are the best hormone for induced breeding

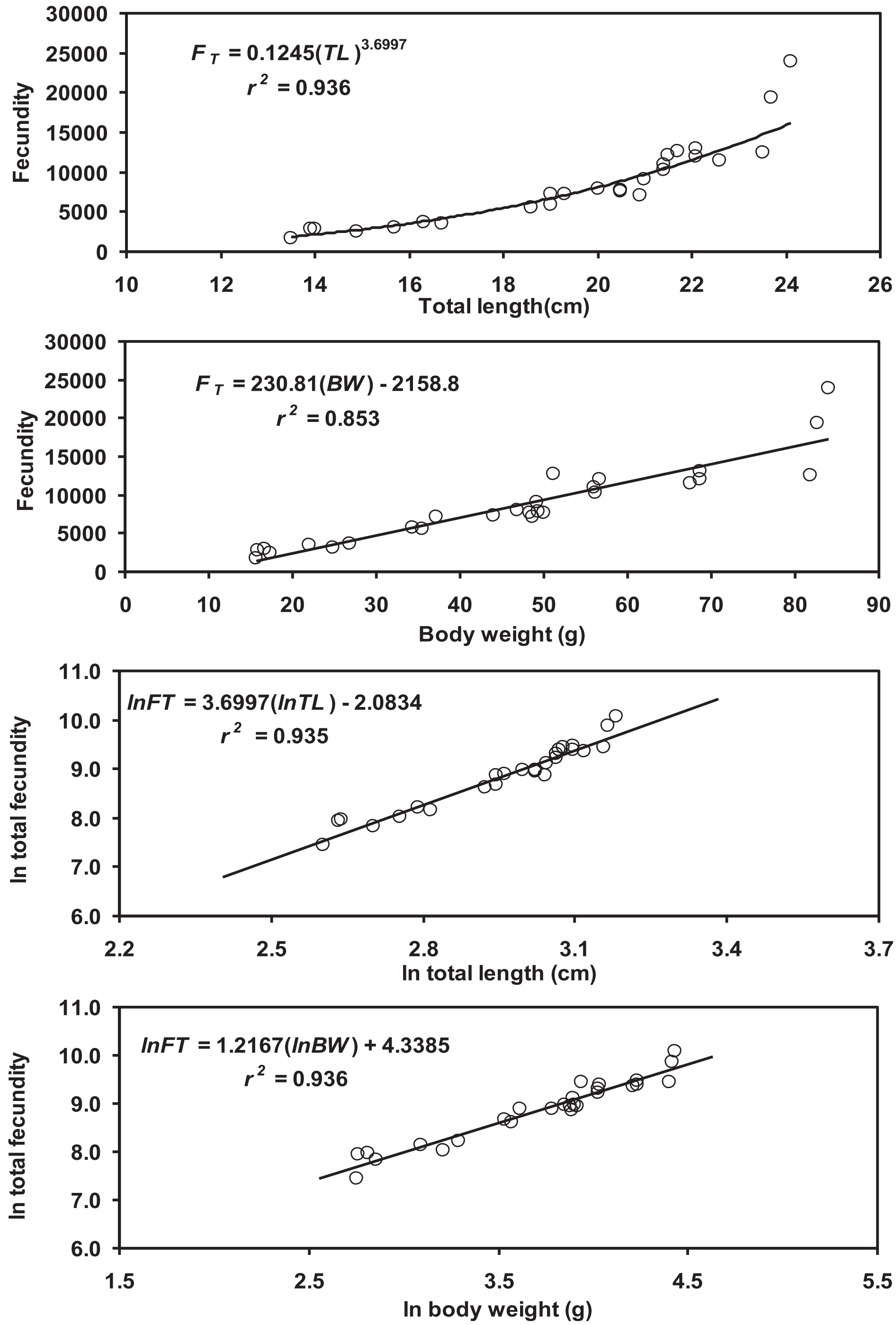

Fig. 8. Relationships between TL *vs.* F_T and *BW vs.* F_T and ln (TL) *vs.* ln (F_T) and ln (*BW*) *vs.* ln (F_T) of female *Heteropneustes fossilis* in the Gajner *Beel*, NW Bangladesh.

Table 7
Relationship between hydrological parameters with GSI of *Heteropneustes fossilis* (Bloch, 1794) in the Gajner *Beel* of northwestern Bangladesh during January to December 2019.

Relationship	r_s value	95% CL of r_s	*p* values	Significance
Temperature *vs.* GSI	0.8182	0.4450 to 0.9492	0.0019	*
DO *vs.* GSI	−0.8392	−0.9555 to −0.4972	0.0011	*
pH *vs.* GSI	0.8266	0.4657 to 0.9518	0.0015	*
TDS *vs.* GSI	−0.5068	−0.8351 to 0.1399	0.1075	*ns*
Total alkalinity *vs.* GSI	−0.9231	−0.9794 to −0.7337	<0.0001	*

GSI, Gonadosomatic index; DO, Dissolved Oxygen; TDS, Total Dissolved Solids; *r*, Spearman rank correlation values; CL, confidence limit; *p*, shows the level of significance; *ns*, not significant;
* significant ($p \leq 0.05$).

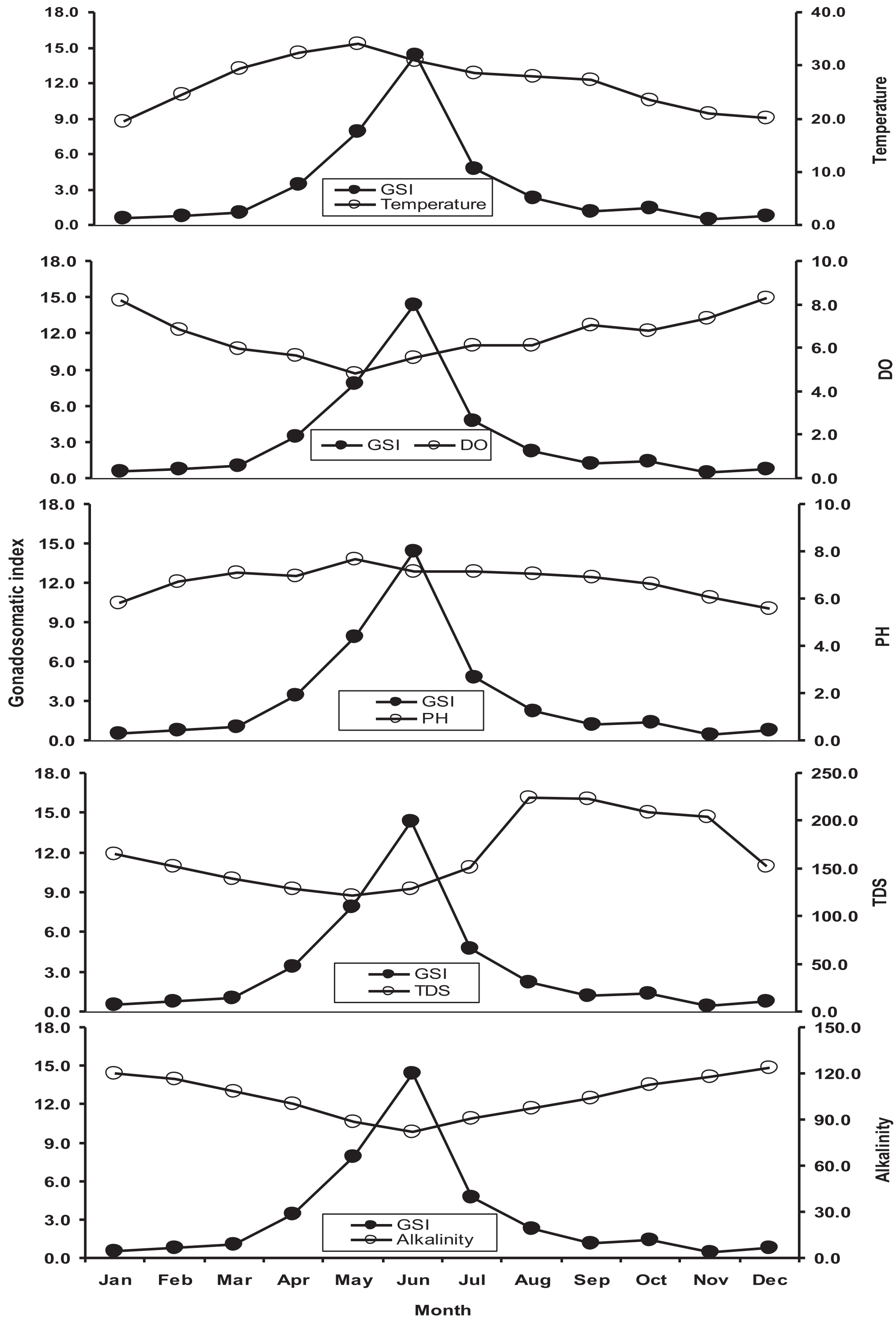

Fig. 9. Relationship between gonadosomatic index (GSI) and different hydrological parameters of female *Heteropneustes fossilis* in the Gajner *Beel*, NW Bangladesh.

of *H. fossilis* than other hormones. But different researcher used different dose of ovaprim among them we recommend 0.7 ml/kg body weight is best dose for induced breeding of *H. fossilis* fish based on highest fertilizing and hatching rate (Table 8). Reproductive performance, development, feed efficiency and feed intake of fish, normally regulated by a few environmental variables. Here we detected optimum range of some environmental factors (temp was 29 to 31 °C, DO was 5.0 to 6.0 mg/l, and pH was 7.1 to 7.5) which can be applying in hatchery for artificial breeding and also can be used in nursery pond for better growth of fingerlings. Mixed diet (commercial feed and snail meat) is the best for highest growth of *H. fossilis* larvae.

4. Discussion

The study exposes the reproductive feature (sexual maturity, spawning season and fecundity) condition, prey predator status and described the relation within reproductive features and eco-climatic factors. It also deals with the optimum range of

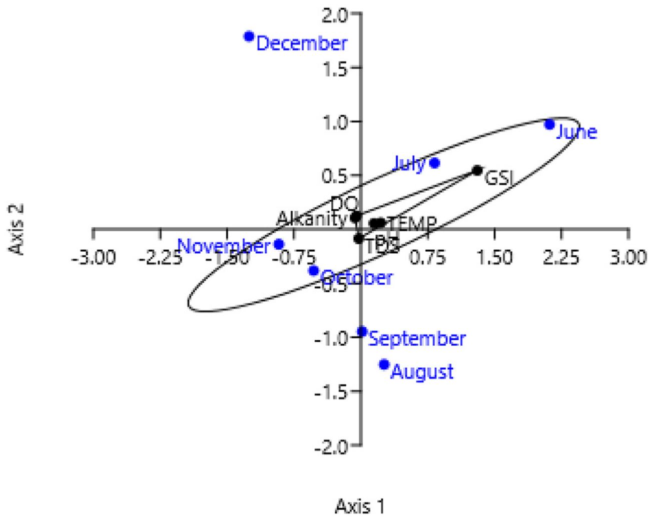

Fig. 10. Correlation of environmental parameters and gonadosomatic index (GSI) of *Heteropneustes fossilis* in Gajner *Beel*, northwestern Bangladesh.

eco-climatic factors in relation to reproduction of *H. fossilis* using multiple indices. As a widely used tool for fisheries biologists and managers, careful estimation of the maturity status of fish, helps to ensure proper assessment and management of exploited stocks (Rahman et al., 2018). Nevertheless, the size at sexual maturity and spawning season of fish were estimated by several models including brooding of eggs over time, appearance of ovary and maturation stages over time (King, 2007), relative weight of gonad (TL *vs.* gonadosomatic index, modified gonadosomatic index and dobriyal index) over time (Hossain et al., 2017a; Ahamed et al., 2018; Khatun et al., 2019) and histological analyses (Chelemal et al., 2009; Lucano-Ramírez et al. 2019; Jan and Ahmed, 2019). Though histological analyses of gonads is the best way of assessing maturity, where the facilities are lacking, other biotic parameters can easily be measured as indicators of maturity status, (West, 1990; Lowerre-Barbieri et al., 2011; Khatun et al., 2019). GSI was used effectively by a good number of researchers to assess the maturity status of fish (Fontoura et al., 2009; Khatun et al., 2019). A significant population parameter in the fisheries management of exploited stocks is the size at maturity (Jennings et al., 2001). It is vital for fisheries biologists to manage and conserve a particular fish population in any aquatic ecosystem (Lucifora et al., 1999). In our study, the size at first sexual maturity for *H. fossilis* was estimated by four models. On the basis of observed maximum length $L_{m,}$ which was 14.02 cm. TL *vs.* GSI relationship also provides an efficient maturity assessment (Ahamed et al., 2018; Hossen et al., 2019). Results of our study estimated L_m of female *H. fossilis* as 13.5 cm TL based on GSI in the Gajner *Beel*. Several studies have described the comparative growth of TL and SL, wherever an unexpected intensification in one of these length sections is indicative of sexual development (Yamada et al., 2007; Khatun et al., 2019). The comparative growth frequency of SL changed at 13.0 cm TL in our study which may suggest gonadal maturity. Based on the comparative growth of different body parts, the variation point could generally represent sexual maturity (Gab-Alla et al., 1990; Cha et al., 2004). Finally, we used a logistic model to assess L_m of *H. fossilis*. GSI information for a logistic function is more appropriate for fish species with an unrestricted sampling program (Fontoura et al., 2009). The estimated L_m in our study was 15.0 cm for female *H. fossilis* through the logistic equation. Talwar and Jhingran (1991) reported that L_m of *H. fossilis* was 12 cm, however, the results of our study revealed the L_m for the species ranged between 13 and 15 cm. This dissimilarity can be attributed to sampling (variation in sample sizes or shrinking body size with formalin preservation) or ecologic differences in population densities, food availability or water temperature (Khatun et al., 2019). This study provides comprehensive information about the length at first sexual maturity of *H. fossilis* by four reliable models. The finding can be useful in selecting mesh size of nets and avoid catching smaller fish thus allowing them to spawn (Khatun et al., 2019).

Spawning season is crucial to assess spawning time and migration of a fish population for breeding purpose (Wilding et al., 2000; Khatun et al., 2019). The maximum values of GSI as an indication of spawning season were determined during April to August in our study. Besides, highest GSI values were observed in June that suggests peak spawning for *H. fossilis* in the Gajner Beel. We found same results, based on monthly changes of maturation stages. A number of other studies observed the spawning season of *H. fossilis* in different months - May and August (Shafi and Quddus, 1982), July to August (Joy and Tharakan, 1999) and April to May and peak in April (Saud et al., 2015). Variation among studies may be ascribed to geographic area, fish population densities, environmental parameters (especially water temperature and rainfall), and/or food availability.

Condition factor as an indicator of success of development, reproduction and survival is a quantitative parameter of the well-being of fish that assesses the performance of the present and future populations (Richter, 2007). Fulton's condition factor (K_F) is an index illustrating correlations between biotic and abiotic factors in fish physiological conditions. It indicates the well-being of the population at different points of the development cycle (Angelescu et al., 1958). In the current study, K_F ranged from 0.33 to 0.72 for female *H. fossilis*. Ferdaushy and Alam (2015) and Muhammad et al. (2017) reported that the K_F of this species was 0.96 and 0.48, respectively. In our study, K_F was found to be significantly related with monthly GSI values. The study revealed that the spawning period of *H. fossilis* began in April with a peak in June and ended in August when the upper values of K_F represented their recovery in the Gajner *Beel*, NW Bangladesh.

Relative weight (W_R) is the most widely used index for determining the status of fish in the ecosystem (Froese, 2006). W_R values below 100 for individuals or populations suggest problems such as low prey accessibility or high predator density, whereas values above 100 indicate a prey surplus or low predator density (Rypel and Richter, 2008). In our study, monthly deviation of W_R from 100 in female *H. fossilis* populations revealed the disparity in habitat regarding the abundance of food items and the presence of prey and predator organisms (Anderson and Neumann, 1996) in Gajner *Beel*.

The estimation of the fecundity and explanation of reproductive strategies is essential in fish biology, physiology and population dynamics (Hunter et al., 1992). Fecundity in fishes is a crucial factor to comprehend differences in population size and is very pertinent to fishery management (Rahman et al., 2018; Hossain et al., 2021). In the present study, fecundity of *H. fossilis* was 1730 to 23,870 in the Gajner *Beel*, NW Bangladesh. In the past, varying numbers of fecundity for this fish were observed by different authors – 1375 to 46,737 (Bhatt et al., 1977), 4200 to 15,750 (Rahman, 1989), 2,843 to 44,724 (Shafi and Quddus, 2001) and 2431 to 23,002 (Saud et al., 2015). The variations in fecundity occurred due to difference in habitat conditions and presence of nutrient and physicochemical factors within, stock variations (Ruzzante et al., 1998) and differences in methodological approaches used for fecundity assessment (Alonso-Fernández (2009)).

Global climate change is impacting the fish and fisheries and will continue to do so in the future (Roessig et al., 2004). Most of the studies into the impact of climate change on fish populations

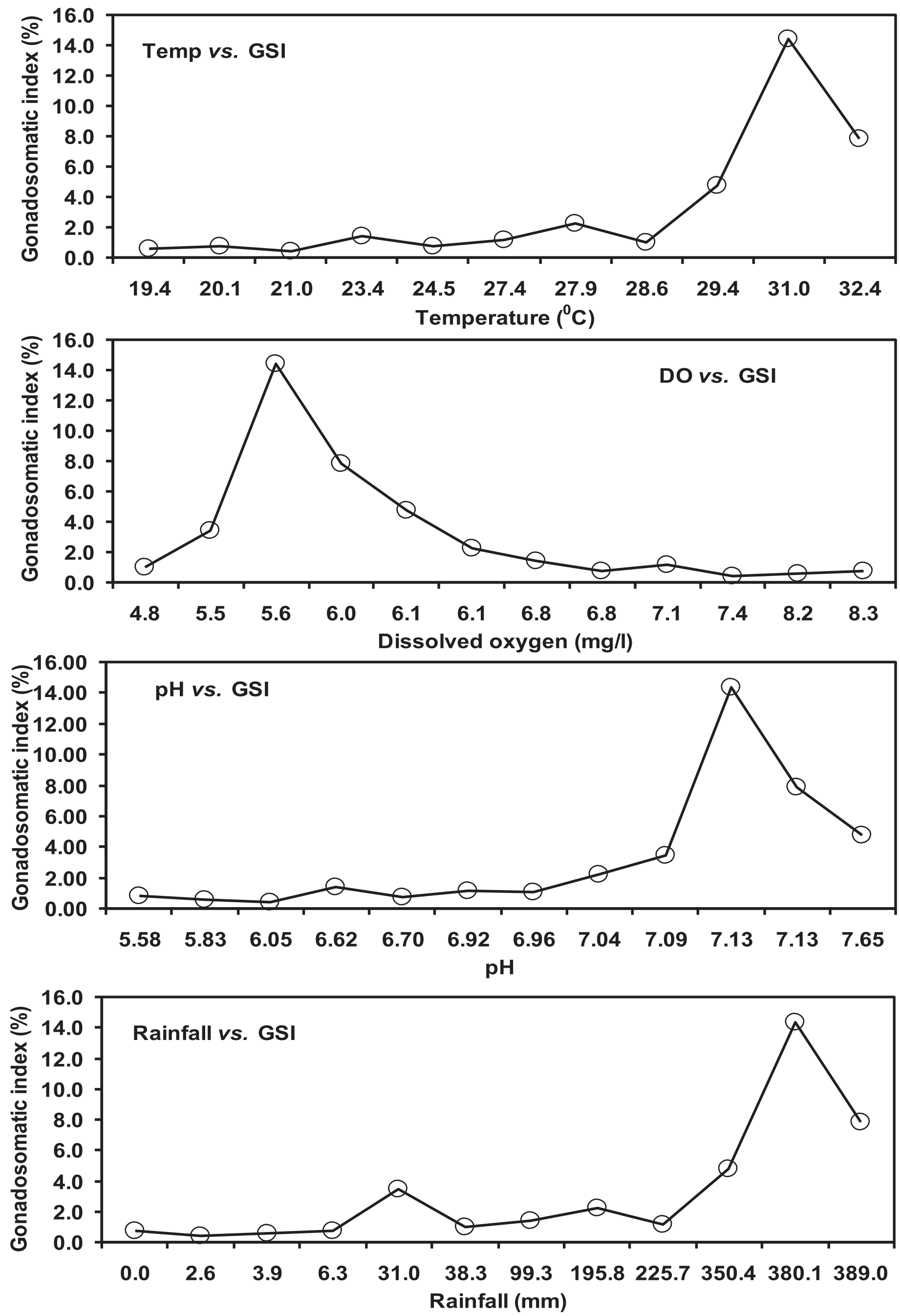

Fig. 11. Determination of suitable eco-hydrological parameters by the relationship between temperature, DO, pH and rainfall *vs.* GSI of *Heteropneustes fossilis* in Gajner *Beel*, northwestern Bangladesh.

have been carried out on pelagic fishes (Loukos et al., 2003; Lloret et al., 2004). Environmental conditions like temperature, DO, pH and total alkalinity affect reproductive migrations of *H. fossilis* in the Gajner *Beel* wetland ecosystem. The maximum GSI values of females were from March to August, when water temperatures were highest, so GSI may be reacting to water conditions as seen for tropical weather fishes in general (Khatun et al., 2019). The impact of temperature in regulating gonadal development and fish reproduction is corporate by various studies (Ridha et al., 1998; Rideout et al., 2005; Khatun et al., 2019). Hence, alterations in peak spawning behavior may result from increasing global temperatures (Peer and Miller, 2014; Khatun et al., 2019). According to our findings, the lowest temperatures were found in January, and the highest was in June suggesting a substantial connection between water temperature and spawning season. The GSI values were high in April to July when temperatures were 29 to 31 °C. So, 29–31 °C may be best for reproduction. We also found DO, pH and total alkalinity ranges of 5.0–6.0 mg/l, 7.1–7.5 and 90–100 mg/l respectively, from April to July when GSI high. So, these ranges should be optimum for reproduction of *H. fossilis*. No other studies are available for *H. fossilis* to relate to our findings. In contrast, the lowest GSI was found at a water temperature of 25 °C. Primary sex cell and segregation of female gonads stimulated by lower temperature (<20 °C) though Chmilevskiy and Lavrova (1990) is dissimilar to our results. Based on climate data (1971–2019) a thermal increase of 0.029 °C yr^{-1} temperature is apparent

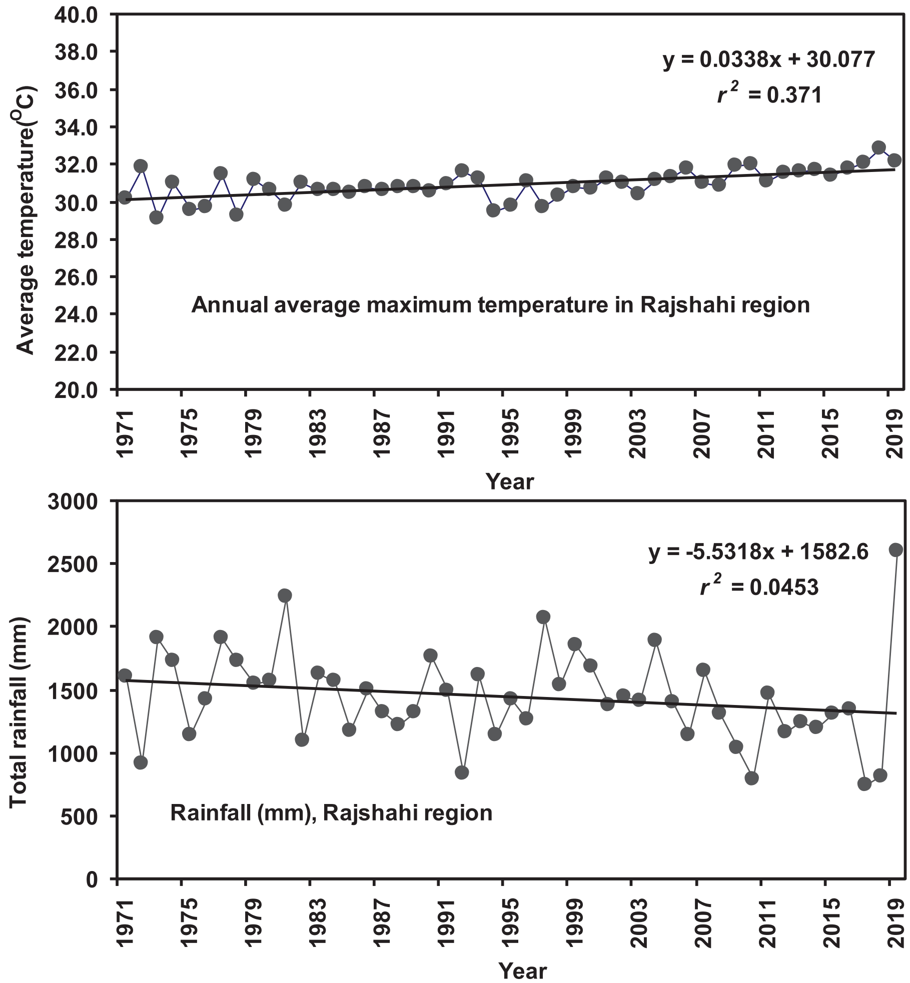

Fig. 12. Annual average maximum temperature (°C) and rainfall (mm) in the Rajshahi region (including Gajner *Beel*) northwestern Bangladesh during 1971 to 2019.

Table 8
Accumulated the optimum parameters from different available works of *Heteropneustes fossilis* on aquaculture aspect.

Aspects	Comparison parameter				Reference
Stocking density	Quantity	SGR%	Survival%	Production (Mean)	
	1,85,000/ha	1.23 ± 0.021	71.61 ± 3.17	9708.16 ± 421.40	Rahman et al. (2014)
	1, 25,000/ha*	2.36 ± 0.16	87	4537.12 ± 227.4	Roy et al. (2019)
	24000/ha (Poly culture)	1.29 ± 0.02	81.78 ± 0.65	693.42 ± 3.08	Hossain et al. (2018)
Feeding	Feeding rate	Feeding frequency	SGR (%)	FCR	
	12–4%	Twice/day	1.23 ± 0.021	2.51 ± 0.04	Rahman et al. (2014)
	12–5%*	Twice/day*	1.23 ± 0.04	1.60 ± 0.01	Nushy et al. (2020)
Protein level	DP (%)	SGR (%)	PER	PRE (%)	
	40*	1.76	1.75	31.7%	Siddiqui and Khan (2009)
Optimum ration level	Ration level (BW day^{-1})	(FCR)	PRE (%)	ERE (%)	
	5*	1.59 ± 0.03	30.8 ± 0.03	59.73 ± 0.24	Khan and Abidi (2010)
Induced breeding	Ovaprim	Time	Fertilization %	Hatching rate %	
	0.5 ml/kg	10	–	82.48	Vijaykumar et al. (1998)
	0.4 ml/kg	10-			
12	–	96	Nayak et al. (2001)		
	0.5 ml/kg	18–24	75.0	60	Haniffa and Sridhar (2002)
	0.5 ml/kg	–	92.33	94.87	Karl Marx and Chakrabarty (2007)
	0.6 ml/kg	10	86.67	76.92	Rahman et al. (2013)
	0.7 ml/kg*	–	93.6	95.5	Arcockiaraj et al. (2001)

* Indicated the best. DP, Dietary protein; SGR, Specific growth rate; PER, Protein efficiency ratio; PRE, Protein retention efficiency; FCR, feed conversion ratio; PRE, Protein retention efficiency; ERE, Energy retention efficiency.

in northwestern Bangladesh. The start of sexual maturity is controlled by environmental and climate driven conditions. Spawning events are normally associated with climatic variability, particularly for rainfall and temperature (Parkinson et al., 1999; Wilding et al., 2000; Khatun et al., 2019; Sabbir et al., 2021). Usually, the annual rainfall sequence of the seasonal tropics is linked to the timing of spawning for Southeast Asian cyprinids (Rainboth, 1991). The maximum rainfall was perceived in April to July in our study, when GSI value was at apex suggesting a connection between GSI and rainfall. The maximum rainfall was reported in June (380 mm) when GSI was highest. GSI was also lowest when rainfall was lowest in January, when no reproduction was occurring. Fluctuation in the spawning season for *H. fossilis* is predicted by exploration of climate data (1971–2019) which showed that rainfall is decreasing by 2.96 mm/year in northwestern Bangladesh. Absence of information prevents comparisons of our findings. But for a temperate freshwater teleost, Parkinson et al. (1999) reported that the high rainfall and temperature influenced final maturation of gonads and spawning season which is similar to our findings. Also increase of air temperature has impact on ecosystem and catfish fishery such as changes in ecosystem, blockage of migratory route and high turbidity of water (Khatun et al., 2019; Sarkar et al., 2020).

We suggest that stocking density 1, 25,000/ha is the best for *H. fossilis* whereas Rahman et al. (2014) suggested 1, 85,000/ha. We found 0.7 ml/kg ovaprim is the optimum for induced breeding of *H. fossilis*. According to Nayak et al. (2001) the best dose is 0.4 ml/kg. Vijaykumar et al. (1998), Haniffa and Sridhar (2002) and Karl Marx and Chakrabarty (2007) revealed 0.5 ml/kg is the best dose for *H. fossilis* induced breeding.

5. Management policies

The management of fisheries is aimed at optimizing the advantages of the unit of output (fish stock) that is being managed. Based on our study outcomes, some management policies are suggested here for the sustainable management of *H. fossilis* in the wetlands of Bangladesh and in the region. For instance, the L_m was 13.0 to 15.0 cm of *H. fossilis* in the Gajner *Beel*, NW Bangladesh that's mean 50% fishes spawn at this length, so smaller sized fishes than the L_m are strongly prohibited to catch and only bigger than 15.0 cm fishes are recommended for exploitation. Banned period should be established based on peak spawning season. In that time fishing would be strictly prohibited. The suitable range of K_F (0.33–0.72) should be maintained in hatchery for artificial breeding of this species. Warming temperatures may be causing earlier river flow pulses which may be responsible for the changes in breeding pattern of fishes (Sarkar et al., 2019). We found that temperature was increasing and rainfall was decreasing day by day with an obvious impact on the shifting of the spawning season of *H. fossilis* so, short term management policies should be established for the management and conservation of the wild stock of this species.

6. Conservation strategies

To protect the diversity of catfishes, numerous measures have been implemented, including in situ conservation, habitat fingerprinting, ex-situ conservation, and the development of live gene banks (Sarkar et al., 2012). We should also restore wetlands because they are an important aspect of the riverine ecosystem, and fish survival is largely dependent on the quality of water bodies. Due to extensive siltation, several wetlands have already lost their link to the main waterway. Fishes use wetlands as breeding and rearing grounds so, research efforts should be translated into action in order to restore those crucial habitats.

7. Conclusion

The air-breathing stinging catfish (*H. fossilis*) is considered to be highly nourishing, palatable and tasty and well preferred because of its less spine, less fat and high digestibility in many parts of Indian subcontinent. Attempt has been taken to describe the changes in reproductive biology, relation to eco-climatic factors and suggesting a policy for aquaculture, conservation and management of *H. fossilis.* In fine, to conserve the wild stock of *H. fossilis* and to ensure the effective and sustainable management of this important fish, it is essential to set the mesh size of nets and establishment of ban period during peak spawning season through the L_m and spawning season, correspondingly. This is vital for the protection of wild stock of *H. fossilis* in the Gajner *Beel* and other open water bodies. *H. fossilis* seeds can be collected from the natural water bodies, after 2–3 months followed by the peak spawning in June and should be farmed following suggested stocking density, feed, feeding rate, feeding frequency and protein levels ensuring good aquaculture practices. *H. fossilis* broods can be collected during the spawning season and artificially breed in the hatchery using recommended doses of hormone. Analyses of time series data on temperature and rainfall revealed a rising trend of temperature and declining drift in rainfall. These eco-climatic factors play key role in the onset of spawning and entire lifecycle thereafter and are responsible for the shift in the breeding season including spawning peak. Any management policy and conservation guideline such as ban period, gear selectivity, amending or proposing new mesh size of nets – must take into account the impact of the eco-climatic factors to pave the way of successful management of *H. fossilis* in the wetland ecosystem.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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