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ARTICLE

Catch Trend and Stock Assessment of Hilsa *Tenualosa ilisha* Using Digital Image Measured Length-Frequency Data

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Abstract
The annual global average catch shares of the anadromous Hilsa *Tenualosa ilisha* of Bangladesh increased rapidly from 74.5% all through 1984–2013 to 86.7% during the 2010–2015 periods. With a few exceptions, an increasing trend of Hilsa production over the last three decades was found in Bangladesh. Initially three options incorporating digital image measurements were compared to determine the best method for obtaining accurate length data. The length-frequency data measured from digital images showed that Hilsa have a moderate growth rate (K = 0.90 year^{-1}) of up to 58.70 cm (L) TL. High fishing mortality (F = 2.83 year^{-1}) and exploitation level (E = 0.67) suggest a slight overexploitation of the Hilsa fishery; the maximum sustainable yield (MSY) was estimated at 526,000 metric tons/year if the recommended TL at first capture (L_c) of 27 cm is adhered to. The present annual Hilsa catch is about 496,417 metric tons, which indicates the potential benefit of achieving MSY through sustainable fisheries management by regulating mesh size of nets and protecting brood fish. Size distribution of Hilsa within sanctuaries revealed a remarkable presence of juvenile fish during February–March in some areas, which suggests a need to readjust the fishing ban period from March–April to February–March. More fisheries management is necessary to reduce the exploitation level of Hilsa by 17% and at the same time increase the allowable L_c to potentially increase the MSY and CPUE.

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Hilsa *Tenualosa ilisha* (subfamily Alosinae) is an important anadromous clupeid fish found in the Bay of Bengal, the Persian Gulf, and Arabian Sea regions (Rahman 2007). Hilsa is the national fish of Bangladesh and is a highly popular food fish because of its special flavor, attractive appearance, and high socio-economic importance (Fischer and Bianchi 1984; Rahman 2007; Sahoo et al. 2016). This species forms the single most important fishery in Bangladesh, which directly employs about 0.45 million people and indirectly about 2.5 million people (Wahab and Golder 2016) and has an estimated nonconsumptive value between US$167.5 million and $355.7 million per annum (Mohammed et al. 2016). In fact, Hilsa contributes about 10.5% of the 3.87 million metric tons of the annual production of the fishery, which represents approximately 1% of the total gross domestic product of the country (DOF 2016). However, the market demands as well as the exploitation of this species are increasing steadily, which could put this fishery at risk without better understanding their population dynamics needed to improve the management of Hilsa.

Previous studies have mainly focused on the biological aspects of Hilsa and the effects of barrages, dams, weirs, and fences on their migratory movements (Pillay and Rosa 1963; Rahman and Moula 1992; Haldar and Rahman 1998; Ahsan et al. 2014). Similar to the closely related American Shad *Alosa sapidissima*, Hilsa has a diadromous migratory pattern (Rahman and Moula 1992; Walther 2007; Islam et al. 2016a). However, there are also indications that Hilsa also has an amphidromous nature because both mature and immature fish frequently move between fresh and marine waters not only for breeding but also for feeding.

Length-based methods are widely used to assess the population dynamics and stocks of commercially important fish species (Munro 1983; Morgan 1984; Pauly 1984a; BOBP 1987; Sparre et al. 1989; Venema and van Zalinge 1989; Gayanilo et al. 2005; Amin et al. 2008; Glamuzina et al. 2017), including Hilsa (Rahman et al. 1999, 2000; Amin et al. 2002, 2004, 2008; Rahman and Cowx 2008). Some of these works were conducted over a decade ago, but were also specific to certain geographical areas or seasons, which may lead to a fragmentary picture of Hilsa fisheries. Therefore, it is important to not only update their stock status but to also comprehensively analyze their population dynamics because this information would be invaluable for the sustainable fisheries management of Hilsa.

In the present study, digital imaging was used to measure length-frequency data from all major migratory habitats of Hilsa. This investigation appears to be the first to generate information using this technique regarding population dynamics and stock status of Hilsa, and subsequently, a guideline for using this method was developed. This is also the first time that the spatial and temporal size composition of Hilsa in sanctuary, nonsanctuary, and marine habitats were also compared. Based on the findings and lessons learned after reviewing the present management activities, suitable short- and long-term management options are suggested for the sustainable management of the Hilsa fishery in Bangladesh.

METHODS

Catch trend assessment.— The global catch trend was assessed by reviewing the global Hilsa catch data over the last three decades, from 1984 to 2015, from the capture fishery database of the Fisheries and Agriculture Organization of the United Nations (FAO) for Bangladesh, India, Pakistan, Iran, Iraq, and Kuwait. For Myanmar, the Hilsa catch data was unavailable in the FAO database, and therefore the average reported by BOBLME (2010) was used to approximate the share for this country. The Bangladesh share of the total average annual global catch was assessed in two groupings: the average share from the last three decades (1984–2013) and the average share in a recent 5-year period (2010–2015) to determine any recent shifts in global shares.

The annual Hilsa catch trend in Bangladesh was assessed by plotting the total annual catches from the last two and a half decades, from 1990 to 2015, from data produced by the Fisheries Resources Survey System (FRSS) of the Department of Fisheries (DOF). These data are also available in the FAO database.

Sampling.— Length-frequency data for Hilsa were collected throughout the year starting from July 2015 to June 2016 and covered all their major habitats in the migratory channel. This was to ensure a sufficient size representation during the analysis. Hilsa were collected monthly from seven sampling sites: (1) Shariatpur (lower Padma River Sanctuary; 23.316653°, −90.43086°), (2) Chandpur (upper Meghna River Sanctuary; 23.167678°, −90.648551°), (3) Lakshmipur (downriver from upper Meghna River Sanctuary; 22.814863°, −90.785385°), (4) Shabazpur, Bhola (lower Meghna River Sanctuary; 22.69181°, −90.684449°), (5) Barisal (nonsanctuary, Kalabadar River, a tributary of the Meghna River; 22.651969°, −90.509925°), (6) Barguna (marine, southwestern part; 22.017359°, −89.955132°), and (7) Cox's Bazar (marine, southeastern part; 21.452136°, −91.967106°). Locations of all the sampling stations can be viewed by means of mapping software, such as Google Earth Pro (Figure 1).

Out of the three sanctuaries mentioned above, one sanctuary was located in the lower part of the Padma River that stretched 20 km along the catchment area (sampling station 1); two other sanctuaries were located in the upper Meghna River at Chandpur–Laxmipur area stretching 120 km along the catchment area (sampling

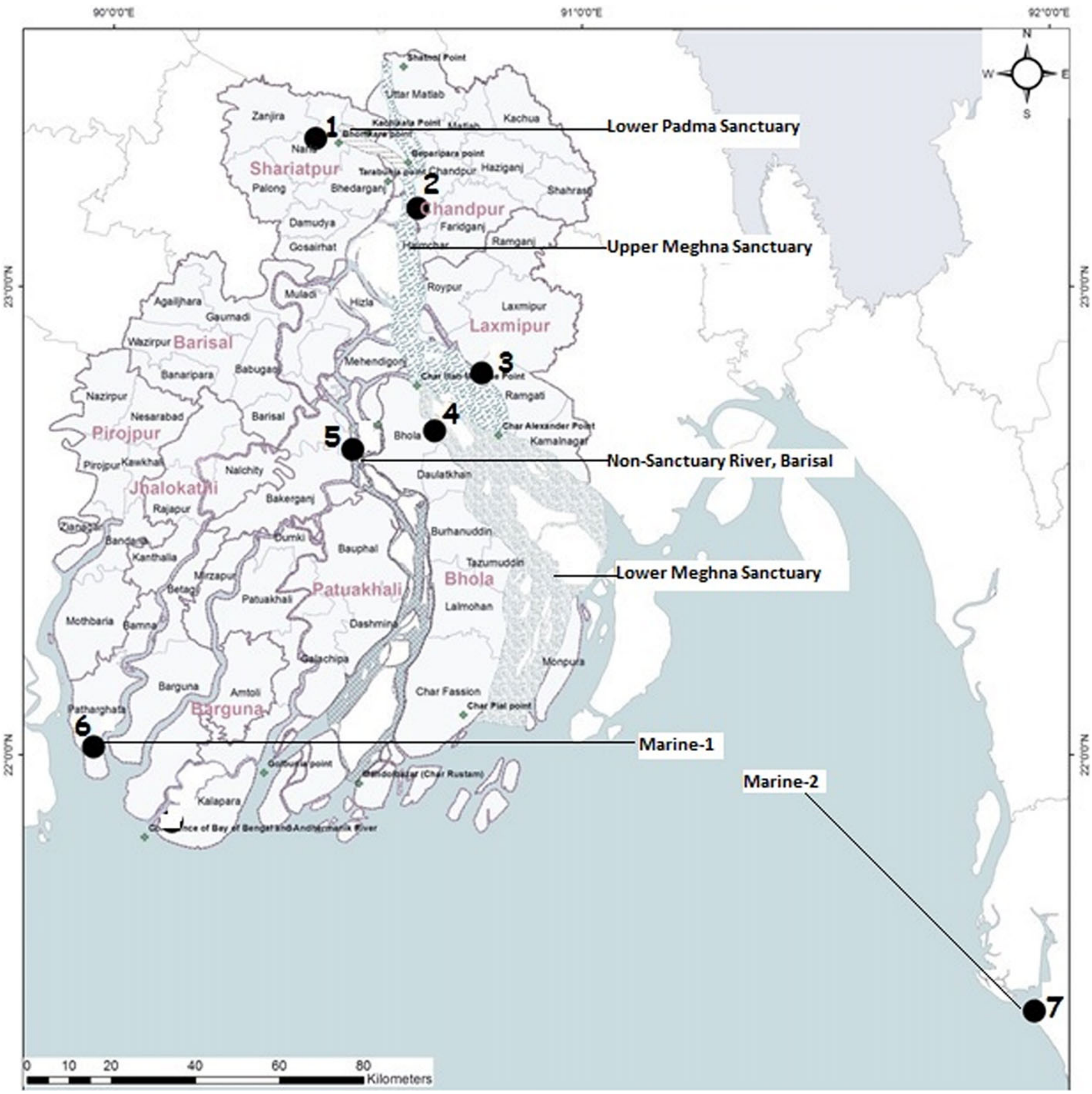

FIGURE 1. Sampling locations (1–7) for length-frequency data collections from Hilsa in the waters of Bangladesh.

stations 2 and 3), and lower Meghna River at Shahbazpur, Bhola, covering 100 km along the catchment area (sampling station 4). The nonsanctuary area was located in the Kalabadar River, which is a tributary of the Meghna River in Barisal (sampling station 5). The marine habitats where representative Hilsa samples were collected were the Barguna and Cox's Bazar marine fish landing stations (sampling stations 6 and 7).

A total of 16,908 individuals (approximately150–200 individuals/month at each station) of mixed-sex Hilsa were measured throughout the year using a novel digital image measuring system, which is described in the next section and shown in Figure 2A. Along with the length, a total of 690 fish were randomly selected, measured for length, and weighed on a digital balance in order to estimate their length–weight relationships.

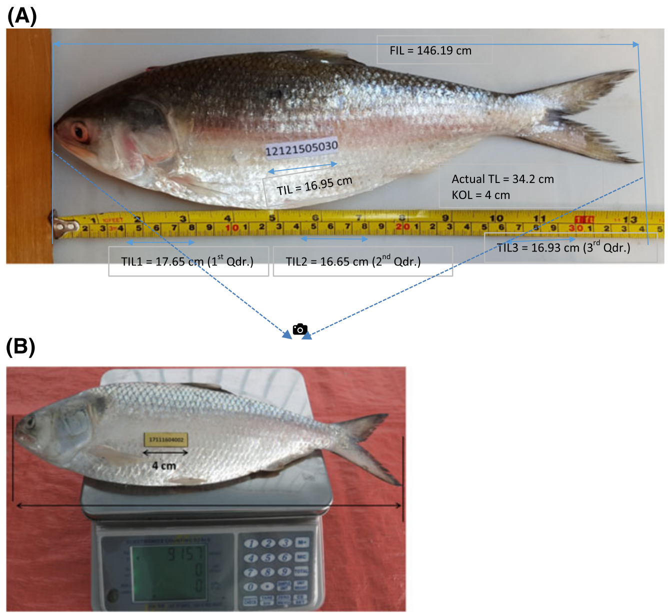

FIGURE 2. **(A)** Image measurements of Hilsa to calculate TL = [(FIL × KOL)/TIL]; FIL = fish image length (cm), KOL = known object length (cm i.e., 4 cm in this study), TIL = tag image length (cm); and **(B)** both length and weight recordings of Hilsa using the same image.

The length-frequency data were collected monthly from these areas and were pooled to obtain a single representative sample for each month to assess the stock. However, annual and monthly size distributions of fish collected from sanctuaries were also analyzed to determine any potential differences in their size distribution among sanctuary, nonsanctuary, and marine habitats.

Fish measurement.— The TL of individual fish was measured from digital photographs. This is the first time a digital image measuring technique has been used for any fish species, and therefore different ways to measure the fish were explored and analyzed, and compared with the traditional system that uses a measuring board. To accomplish this, 30 individual fish representing different sizes were measured using the traditional method as well as three image-measuring options and then the results were compared.

In the first option, the image was taken along with one or three tags, as shown in Figure 2A. The first tag, which was used in all photographs, was a 4-cm-long paper tag containing a code number that identified the individual and the place and date of capture. Three of the paper tags with code numbers were placed approximately at the end of the first, second, and third quadrate positions as marked on a scale to determine whether the placement of the tag had any effect on the accuracy of measurements. An image was then taken from a location that focused on the whole body of the tagged fish as the object (Figure 2A).

The next step was the measurement of the fish image length (FIL) and tag image length (TIL) as shown in Figure 2A. The FIL and TIL were measured from the image using Adobe Illustrator software, and the TL of fish was calculated using equation (1):

$$\mathrm{TL} = (\mathrm{FIL} \times \mathrm{KOL})/\mathrm{TIL}, \tag{1}$$

where TL is the total length of the fish (cm), FIL is the fish image length (cm), KOL is the known object length (cm; e.g., 4-cm paper tag), and TIL is the tag image length (cm).

In the second option, each individual fish was placed on the L-shaped measuring board with the snout touching the vertical portion or on a measuring tape with a code number to identify the individual fish, place, and date as shown in Figure 2A. Then, a digital image was taken focusing on the caudal side of the fish so that the TL could be read directly from the image.

The third option measured both the length and weight at the same time using a single image of fish using option 1 on a digital weighing scale, and the weight was recorded directly from a digital display window (Figure 2B). This allowed the user to simultaneously record the weight and length without the need for extra paperwork.

The TL obtained from the three image options were compared statistically with the TL of the same fish measured using the traditional approach using a paired-sample *t*-test to determine the most accurate image-measuring option. To assess the validity of the image-measuring options, a 34.2-cm-TL fish along with a scale with all the options were measured and compared.

Spatial and temporal size distribution.— The spatial size distribution of Hilsa was assessed by plotting the length-frequency data for the three sanctuary, one nonsanctuary, and the two marine habitats. The temporal size distribution was assessed monthly as well as annually for each of the six habitats.

Length–weight relationship.— The parameters a and b of the length–weight relationship was estimated from the length and weight data using equation (2):

$$W = aL^{b}, \tag{2}$$

where W is the weight of the fish, L = length of the fish, a is the intercept, and b is the exponent.

Growth and population parameters estimation.— To estimate growth parameters, the von Bertalanffy growth equation was used, which expresses the length, L, as a function of fish age, t, as shown in equation (3):

$$L_t = L_\infty\{1 - e^{[-K(t-t_0)]}\}, \tag{3}$$

where L_∞ is the length of infinitely old fish, or asymptotic length (cm), K (year^{-1}) is a curvature parameter that determines how fast the fish approaches L, and t_0 (sometimes called the initial condition parameter) determines the point in time when the fish has zero length. The asymptotic length (L_∞) and growth constant (K) were estimated using the ELEFAN I (electronic length-frequency analysis) routine of the FiSAT II that was applied to the length-frequency distributions to estimate the growth parameters and fit the growth curves (Gayanilo et al. 2005). After obtaining the estimated growth parameters, the growth performance index, Munro's phi prime (φ') (Munro and Pauly 1983; Pauly and Munro 1984), was estimated using equation (4):

$$\varphi' = \log K + 2 \log L_\infty, \tag{4}$$

where K and L_∞ were the same as in equation (3). The estimated growth parameters were tested for reliability by comparing the estimated φ' values.

Total mortality (Z) was estimated using the linearized length-converted catch curve method, provided in the FiSAT package, using the von Bertalanffy growth parameters as input data (Gayanilo et al. 2005); this model is discussed in Pauly (1983, 1984a, 1984b). The slope (b) of the curve is $-Z$. Thus, from the length-frequency data, together with the estimated growth parameters K and L_∞, the total mortality (Z) was estimated.

The natural mortality (M) was estimated using Pauly's empirical formula (equation 5) based on growth parameters L and K and the mean annual temperature (T = 27.2°C):

$$\ln M = -0.0152 - 0.279 \ln L_\infty + 0.6543 \ln K + 0.463 \ln T. \tag{5}$$

From the Z and M estimates, the fishing mortality (F; year^{-1}) was estimated using equation (6):

$$F = Z - M. \tag{6}$$

*Exploitation level (*E*) and recruitment pattern.*— From the estimated Z and F, the exploitation level (E) was estimated using equation (7):

$$E = F/Z. \tag{7}$$

The recruitment pattern was determined by plotting the number of recruits in each month using the monthly collected length-frequency data in FiSAT II. This FiSAT routine reconstructs the recruitment pulses from a time series of length-frequency data to determine the number of recruitment pulses per year and the relative strength of each pulse.

Relative yield, steady state biomass (SSB), and maximum sustainable yield (MSY).— The relative yield per recruit (Y'/R) routine of FiSAT II was used in the analysis of the Beverton and Holt model, as modified by Pauly and Soriano (1986). The model produces a Y'/R versus E (=F/Z) and a relative biomass per recruit (B'/R) versus E, from which E_{max} (exploitation rate that produces maximum yield), $E_{0.1}$ (exploitation rate at which the marginal increase of Y'/R is one-tenth of its value at E = 0) and $E_{0.5}$ (value of E under which the stock has been reduced to 50% of its unexploited biomass) were also estimated. The recommended length at first capture (L_c) was estimated at the $E_{0.5}$ level.

The steady state biomass (SSB) was estimated using the length-structured virtual population analysis (VPA)

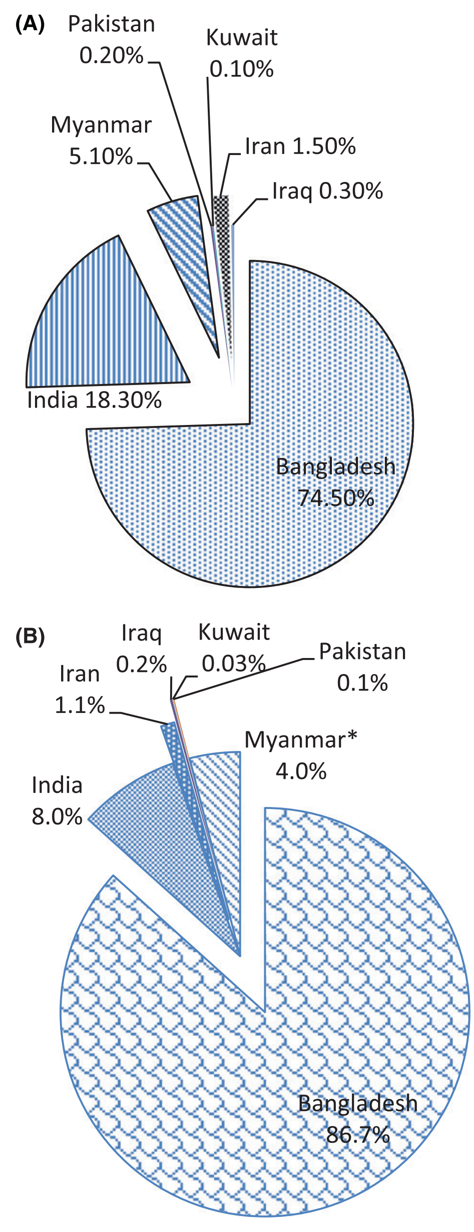

FIGURE 3. Percentage share by country of global Hilsa production: **(A)** average over the last three decades (1984–2013) and **(B)** average of over the last 5 years (2010–2015). Data were compiled from FAO (2017), except for Myanmar for which values were extrapolated from BOBLME (2010) as the data were unavailable in FAO records.

routine in FiSAT II. This routine provides the current biomass as SSB in metric ton for each of the length-classes by converting the number of fish to weight, based on the parameters of the length–weight relationships. Then, the maximum sustainable yield (MSY) of Hilsa was estimated using equation (8) as proposed by Gulland (1971) and further modified by Garcia et al. (1989):

$$\mathrm{MSY} = 0.5\,\mathrm{SSB} \times Z. \tag{8}$$

RESULTS

Catch Trend

Global trend.— The average global Hilsa catch record from the Bay of Bengal region during the last three decades (1984–2013) shares about 97.9% of the world Hilsa catch (Figure 3A). Within this share, Bangladesh contributed about 74.5% of the catch, followed by India (18.3%) and Myanmar (5.1%). The Persian Gulf region shares about 1.9% of which Iran contributed about 1.5% followed by Iraq (0.3%) and Kuwait (0.1%). The main contributor in the Arabian Sea region to the global catch is Pakistan (0.2%). However, in recent years (2010–2015), as shown in Figure 3B, the average annual global shares of Hilsa have shifted mostly to Bangladesh at 86.7%, followed by India, Myanmar, Iran, Iraq, Pakistan, and Kuwait at 8.0, 4.0, 1.1, 0.2, 0.1, and 0.03%, respectively.

Bangladesh.— With a few exceptions, the total annual Hilsa production in Bangladesh increased steadily over the last three decades from 1988 to 2015 (Figure 4). The total production was the lowest at 182,167 metric tons in 1991, while the highest at 387,211 metric tons was recorded in 2015. From 1998 to 2003, the total average catch was 199,550 ± 4.76 metric tons (mean ± SE; range, 182,167–229,714 metric tons), and then in 2004 the total catch increased rapidly to 255,839 metric tons. Afterwards, production increased steadily to 385,140 metric tons in 2014 and remained nearly static up to 2016, and then sharply increased again to the highest amount in 2017 (Figure 4).

Image-Measured Length-Frequency Data

The three options for using digital photographs for TL measurements of individual fish were suitable for different purposes in different situations (Table 1). The first image option (image taken with one or three known objects and codes; Figure 2) had an easy operational advantage. However, when only one object of a known size was used, the length measurements were significantly different ($P < 0.05$) from the traditional measurement method. When three tags were used and placed on the first, second, and third quadrates, the measurements obtained were not significantly different from the traditional measurement system ($P > 0.05$). The second image option (image taken on L-shaped measuring scale with code number) was the most accurate based on these measurements not being significantly different from those using the traditional measurement methods ($P > 0.05$). The third image option (image taken on digital weighing scale and option 1 applied) had a particular advantage of being able to obtain both length and weight data from a single image (Figure 2B; Table 1).

The variation in lengths using the different options was demonstrated by initially measuring a 34.2-cm-TL fish (Figure 2A). Using the four options—one object placed on the middle of the fish body or placed on the first,

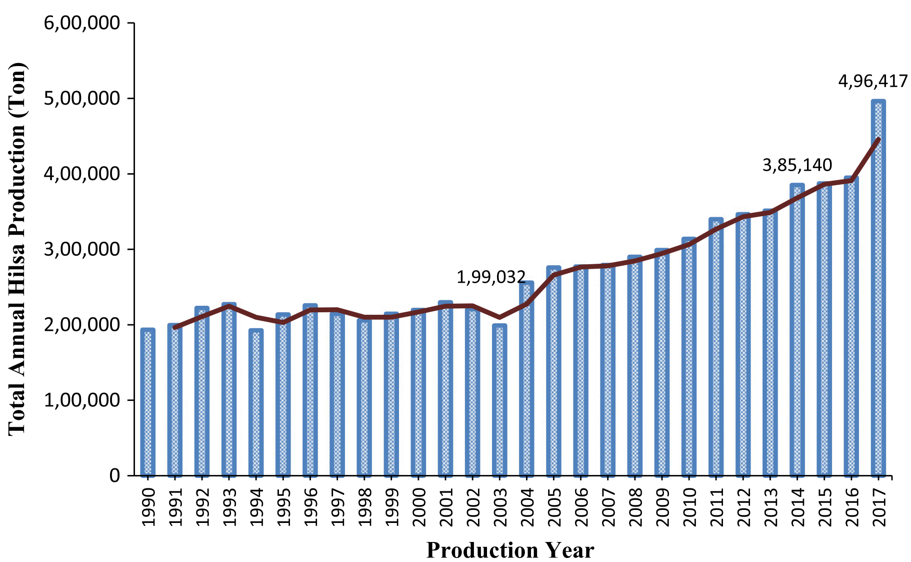

FIGURE 4. Trend of annual Hilsa production in Bangladesh during the last two and a half decades from 1990 to 2017. The trend line is fitted from the moving average (data source: FAO 2017 and DOF 2017).

second, or third quadrate—the measurements were 34.5, 33.1, 35.1, and 34.5 cm TL, respectively. The average from the last three quadrate-based measurements was 34.2 cm, which was the same as the actual TL of the fish. However, when using a single object, the TL of the same fish was slightly different (34.5 cm) from the actual value. The use of three objects for the measurements provided more accuracy than the single-object measurement (Table 1). Using the second option, fish length was recorded directly from the image of the measuring scale along with the image of the fish.

Spatial and Temporal Size Distribution

The size range covered from 10 to 50 cm TL, but fish size showed differences among the five habitats. The most remarkable difference was observed in the lower Meghna

TABLE 1. Advantages and disadvantages of length-frequency and weight data collection using different digital image measuring options compared with the traditional technique.

Option	Advantage	Disadvantage	Remarks
Traditional measurement using L-shaped measuring board.	• Data recorded on paper, so instantly available for use. • No image-taking equipment necessary. • Well-known and minimum technical knowledge necessary.	• Once a mistake is made, the measurement cannot be rechecked. • Considerable fish handling necessary. • Data recording on paper in the field needs extra assistance. • Once finished, no other measurement can be obtained from the same fish.	• Fish placement and length recording need to be done carefully to improve accuracy.
Image option 1: Image taken with one or three known objects and codes (Figure 2B).	• Fish need less handling compared with the traditional way. • Easy as no measuring board necessary. • Paperless data recording in the field, so recording assistance not necessary. • The measurement can be rechecked and mistakes can be corrected. • Many other measurements (e.g., FL, head length) can be done when necessary using the same fish image. • Data collector, fishers, and fish owners in the field are more likely to better cooperate to take photographs. • Can be used as a tool to monitor field data collection.	• Data retrieving is time consuming and needs software and skill. • Photographic equipment (camera/smartphone) as well as storage devices necessary.	• Use of three known objects instead of one can improve the accuracy through minimizing the effect of camera angle, and in case of one known object the longer the length of the object, the better the accuracy.

TABLE 1. Continued.

Option	Advantage	Disadvantage	Remarks
Image option 2: Image taken on L-shaped measuring scale with code number.	• Most reliable and self-validated recording as it can provide the image of the record. • Paperless data recording in the field, so recording assistance not necessary. • The measurement can be rechecked and mistakes can be corrected. • Many other measurements (e.g., FL, head length) can be done when necessary using the same fish image. • Data collector, fishers, and fish owners in the field are more likely to better cooperate to take photographs. • Can be used as a tool to monitor field data collection.	• Fish handling and measuring board necessary, similar to the traditional method. • Other disadvantages of option 1 applicable to this option	• Most accurate and self-validated method
Image option 3: Image taken on digital weighing scale and option 1 applied.	• Both length and weight can be recorded at same time for same fish. • Other advantages of option 1 applicable to this option.	• Disadvantages of option 1 applicable to this option.	• Most convenient for length and weight data collection.

sanctuary, where, unlike the other habitats, juveniles as small as 10–14 cm TL were present in relatively high numbers (Figure 5). However, some undersized fish that were <25 cm TL, referred to as "Jatka" in Bangladesh, were present in all habitats. The main bulk of the catch was in a size range of 26–34 cm TL, and marine catches

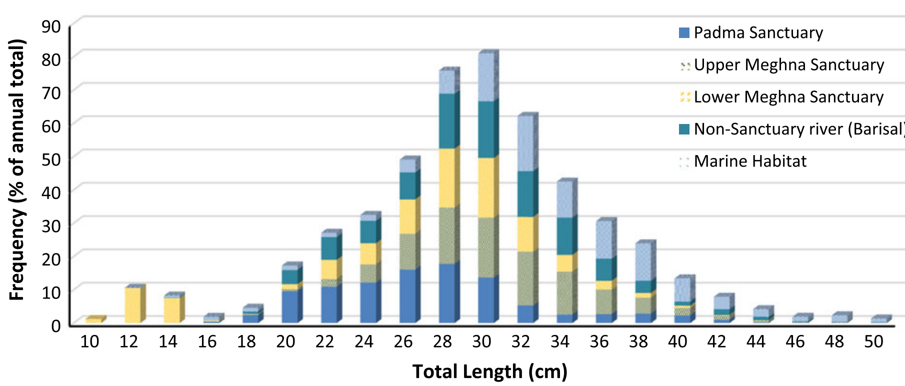

FIGURE 5. Annual size distribution of Hilsa in three sanctuaries, a nonsanctuary river, and marine habitats in Bangladesh during July 2015–June 2016.

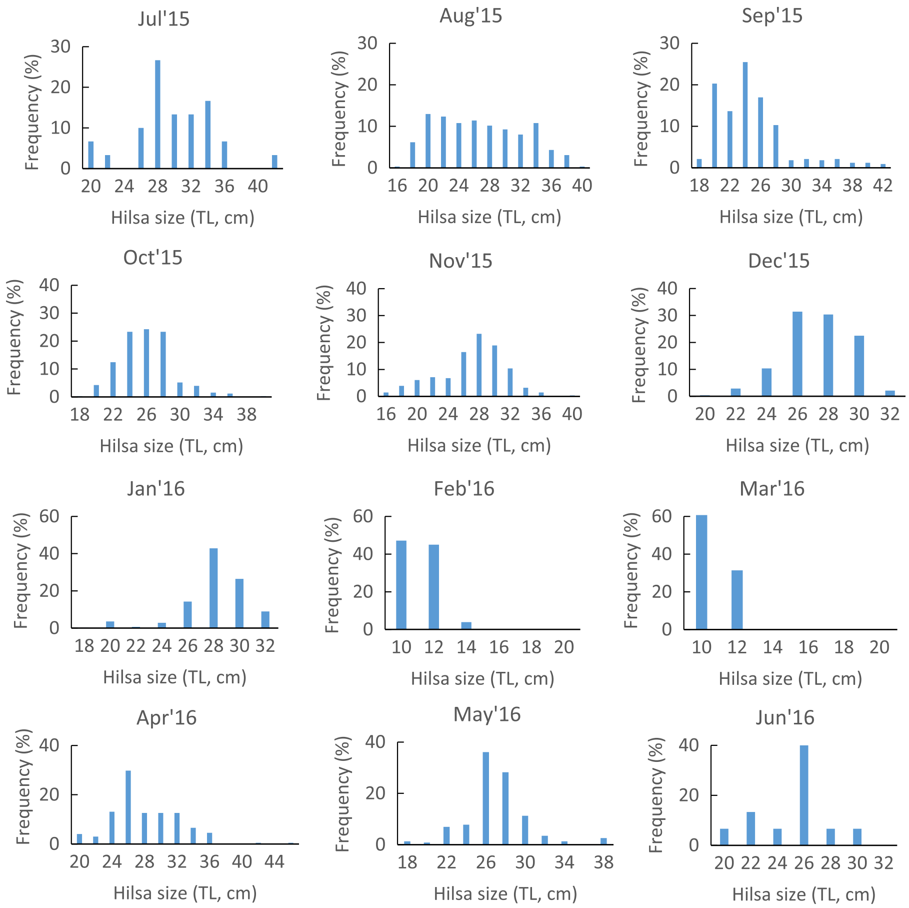

FIGURE 6. Monthly size distribution (TL, cm) of Hilsa in the lower Meghna sanctuary (Shabazpur, Bhola) in Bangladesh during July 2015–June 2016.

covered the widest size ranges (Figure 5). The most small-sized juveniles were recorded in February–March in the lower Meghna sanctuary, but there were no remarkable monthly size differences observed among the other habitats (Figure 6).

Length–Weight Relationship

The parameters a and b in the length–weight relationship for Hilsa were estimated from the length and weight data using equation (2), and the length–weight relationship was calculated as $W = 0.0368L^{2.717}$. These values were used as input data to convert length to weight by estimating the SSB of Hilsa.

Growth and Population Parameters

Based on the output from equation (3), the estimated von Bertalanffy growth parameters were 58.7 cm TL for L_∞ and 0.90 year^{-1} for K (Table 2), indicating that Hilsa can grow up to a maximum of 58.7 cm TL if not caught by fishing activities. The estimated growth performance index φ' from equation (4) was 3.5 (Table 2). The superimposed growth curves of the length-frequency distributions are shown in Figure 7, which revealed the presence of six growth curves. This indicates the presence of six cohorts or size-groups in the Hilsa population.

The estimated Z based on a linearized length-converted catch curve method was 4.19 year^{-1} (Figure 8). The estimated M using equation (5) was 1.36 year^{-1} when T = 27.2°C. Estimated F calculated from equation (6) was 2.83 year^{-1}, which was higher than M (Table 2).

Exploitation Level, Recruitment Pattern, and Relative Yield per Recruit

Using the estimated Z and F values, the exploitation level, E, was estimated at 0.67, which was higher than the expected range of 0.5–0.6 (Table 2). The recruitment pattern for the Hilsa population was more or less continuous, with two major pulses that deviated from two normal curves (Figure 9). A third pulse was also observed just 2 months after the peak pulse but was not separated by

TABLE 2. Growth parameters (L_∞ and K), mortality and survival parameters (Z, M, F, and S), and fishery parameters (E, L_c, and MSY) of Hilsa in Bangladesh waters.

Description of parameters	Value	Comments
Number of Hilsa used (n) for length samples	16,908	Hilsa length-frequency data cover all major inland habitats as well as marine habitats
Growth parameters		
Asymptotic TL (L_∞)	58.7 cm	Hilsa can grow up to 58.7 cm TL
Growth constant (K)	0.9 year^{-1}	Growth rate is moderate for Hilsa
Growth performance index (φ')	3.50	The value matches with that for other clupeid fishes
Mortality parameters		
Total mortality ($Z = F + M$)	4.19 year^{-1}	Total mortality is very high for Hilsa
Natural mortality ($M = Z - F$)	1.36 year^{-1}	Natural mortality (at 27.2°C) is low
Fishing mortality ($F = Z - M$)	2.83 year^{-1}	Fishing mortality is very high
Fishery parameters		
Exploitation level ($E = F/Z$):		Hilsa fishery little bit overexploited (E = 0.5–0.6 is the acceptable range)
E	0.67	
E_{max}	0.66	
$E_{0.50}$	0.36	
$E_{0.10}$	0.55	
Total length at first capture (L_c)	27 cm TL	The recommended minimum size of Hilsa to catch for obtaining MSY
Maximum sustainable yield (MSY)	526,000 metric tons	Obtainable maximum annual yield of Hilsa if the recommended L_c of 27 cm TL is maintained

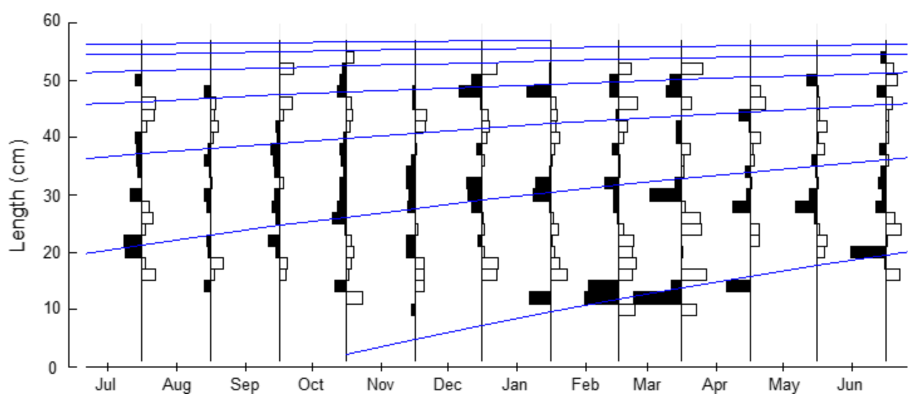

FIGURE 7. The von Bertalanffy growth curves superimposed on the length-frequency distribution of Hilsa in the waters of Bangladesh (L_∞ = 58.7 cm TL, K = 0.90 year^{-1}, Rn = 0.144; the six lines represent six cohorts).

the normal curve. The first pulse appeared in March, the second pulse appeared in May–June, and the third appeared in July–August (Figure 9).

From the relative Y'/R) analysis, the estimated E_{max}, $E_{0.1}$, and $E_{0.5}$ values were 0.61, 0.55, and 0.36, respectively (Table 2). Analysis showed that the maximum yield could be obtained from the Hilsa fishery at an E of 0.61. As indicated in red in Figure 10, 50% of the biomass could be obtained as an annual yield when E = 0.36. The biologically optimum yield following the principle of $E_{0.1}$ could be obtained at E = 0.55 for the Hilsa population.

Steady State Biomass and Maximum Sustainable Yield

From the probability of capture analysis using selection curves, the estimated optimum TL of Hilsa at first capture ($L_c = L_{50}$) was 27.0 cm (Figure 11). The estimated total SSB using the length-structured virtual population analysis (VPA) routine of FiSAT II was 251,100 metric tons

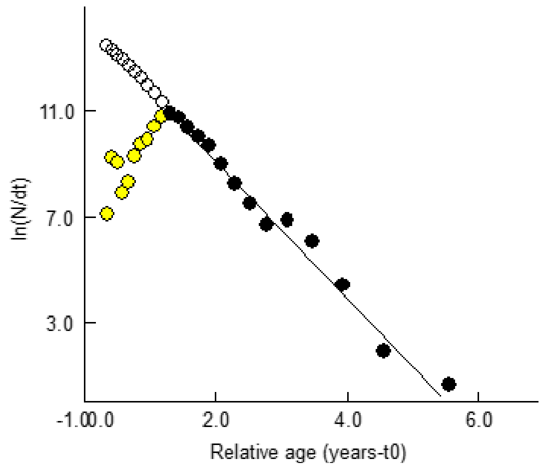

FIGURE 8. Linearized length-converted catch curve analysis to estimate total mortality, Z, from the length-frequency distribution of Hilsa in the waters of Bangladesh (L_∞ = 58.7 cm TL, K = 0.90 year^{-1}, Z = 4.19 year^{-1}, M = 1.36 year^{-1} at 27.2°C).

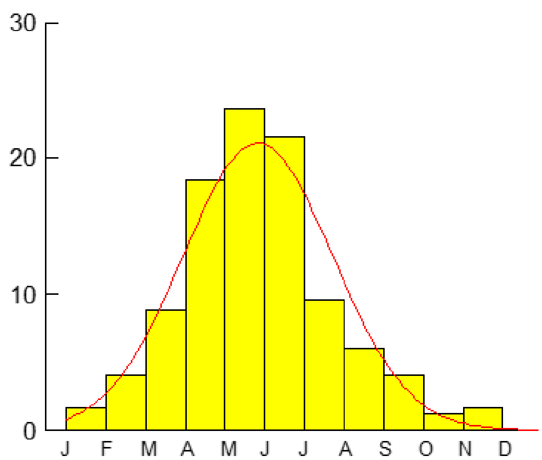

FIGURE 9. Recruitment pattern of Hilsa in the waters of Bangladesh (L_∞ = 58.7 cm TL, K = 0.90 year^{-1}, t_0 = 0.003; Rahman and Cowx 2008).

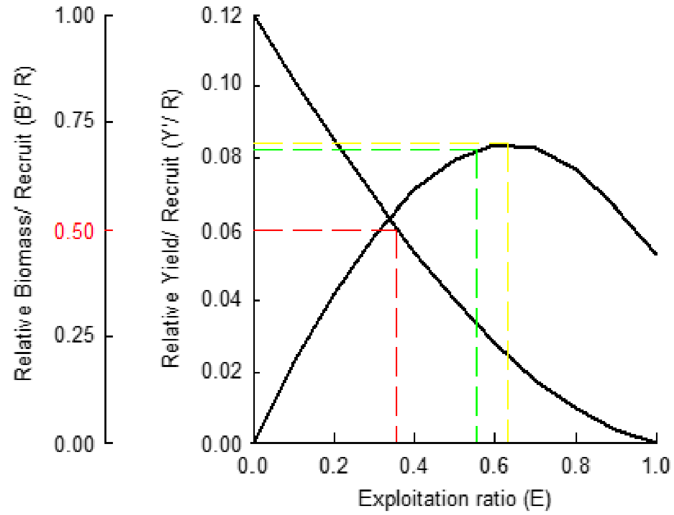

FIGURE 10. Relative yield per recruit (Y'/R) and relative biomass per recruit (B'/R) analyses of Hilsa in the waters of Bangladesh (L_∞ = 58.7 cm TL, M/K = 1.51).

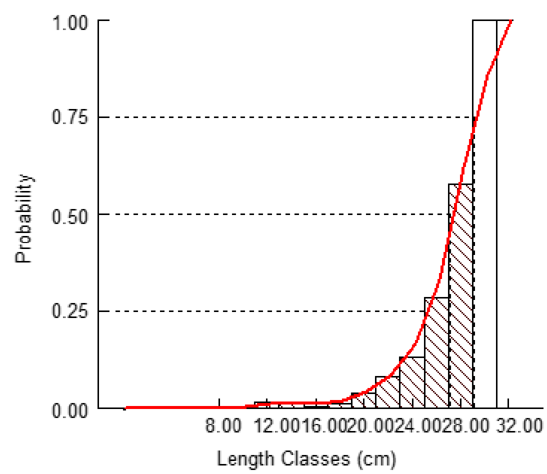

FIGURE 11. Plot of probability of capture against length-classes of Hilsa to estimate length at first capture ($L_c = L_{50}$ = 27 cm TL) in the waters of Bangladesh (L_∞ = 58.7 cm TL, K = 0.90 year^{-1}).

(Table 3). The SSBs for each size-class are also shown in Table 3, which shows the changes in population number and SSB with size. The MSY of Hilsa was estimated at 526,000 metric tons, if the recommended length at first capture (L_c = 27 cm TL) is maintained.

DISCUSSION

All major size-classes of Hilsa available in all major habitats of the commercial fisheries were included in this study. Moreover, a robust number of samples (from 16,908 individuals) were obtained year round for measuring their length frequency distribution. Although there are some phenotypic variations in Hilsa between different river systems in Bangladesh, genetic studies indicate this comprises a single stock (Kuldeep et al. 2004; Salini et al. 2004). These factors indicate that the collected samples would be representative of the stock and sufficient for a comprehensive length-based stock assessment of this commercially important species.

Image Measurement

Image measurements can be particularly useful when large numbers of samples are collected in the field at one time, as in this study. However, to obtain accurate measurements of TIL and FIL there are two important considerations: object placement, angle, and distance to the camera and the number of objects used for reference. For the latter, one object could be sufficient for practical purposes such as in the field. However, the use of three objects provides more accurate results based on the requirements for many imaging software programs, for example, Adobe Illustrator. A 100% direct, self-validated, length record could be obtained using the second image option, i.e., when images are taken by placing the fish on the L-shaped measuring board and reading the length from the obtained image. The third option is only applicable when both length and weight data are necessary at the same time, and a digital scale for measuring weight is available in the field (Table 1).

After choosing a suitable option for image taking and measuring after considering the guidelines in Table 1, this method can be used as a field monitoring tool, which will facilitate data collection by minimizing handling and paperwork. In addition, many other measurements from one image, such as FL, SL, head length, and body depth, for example, could be obtained later in the laboratory. Therefore, image measurements could provide the researcher with a more efficient method for collecting and monitoring length-frequency and length-weight data during fisheries research.

Fork length measurement of Hilsa sometimes becomes difficult as the two caudal lobes are most often found separated and folded, resulting in extra subjective error despite using the digital image measurement system. Royce (1942) found that the weight could be estimated more accurately from the TL than from the SL, and the length–weight relationship is a factor in length-based stock assessment, so, TL was measured and used. Moreover, most of the previous length-based works on Hilsa were conducted using TL, so TL was used to compare the present findings with those obtained in the past.

The Matlab image-processing software can also be used for image measurement. This software is especially suitable for more complex engineering and multidimensional geometrical measurements, and we found it difficult to teach our field level researchers and data collectors how to use this program. However, this study is not restricted to the use of the Matlab software; rather this method will open more doors to easy ways for measuring fish lengths by field-level researchers.

TABLE 3. Population number ($N \times 10^6$) by size (TL) and steady state biomass (SSB) of Hilsa at different levels of fishing mortality (F) in Bangladesh waters.

Length (TL, cm)	Population ($N \times 10^6$)	Fishing mortality (F)	Steady state biomass (SSB) (metric tons)
2	1,580.48	0	34.85
4	1,498.43	0	197.61
6	1,417.88	0	568.42
8	1,338.85	0	1,206.43
10	1,261.36	0.0186	2,156.8
12	1,184.45	0.1657	3,441.38
14	1,101.49	0.1511	5,069.28
16	1,021.76	0.0497	7,075.22
18	949.47	0.0797	9,468.8
20	877.68	0.24	12,171.03
22	800.62	0.4107	15,049.23
24	719.20	0.5621	17,966.65
26	635.88	1.042	20,541.73
28	540.08	1.8401	21,986.46
30	428.38	2.7158	21,614.52
32	312.40	3.3027	19,512.33
34	211.88	3.4999	16,484.8
36	136.80	3.9693	13,011.08
38	81.17	4.8855	9,169.07
40	41.49	5.2227	5,678.32
42	18.96	5.5978	3,119.53
44	7.50	2.83	45,585.75
Total SSB:			251,109.29

Spatial and Temporal Size Distribution

The presence of small-sized juveniles (10–14 cm TL) in February in the lower Meghna sanctuary indicates that the Jatka season starts a month earlier (February–March) in this sanctuary than normal (March–April), which is when the fishing ban period applies. This finding indicates that a more effective management strategy may be to shift the ban period from March–April to February–March in this highly important coastal sanctuary. However, further investigations should still be conducted on when and where the most effective 2-month fishing ban period for Hilsa should be implemented.

Growth and Population Parameters

The growth parameters of Hilsa populations from other studies in Bangladesh waters varied widely (BOBP 1987; Miah et al. 1997; Rahman et al. 1999, 2000; Rahman and Cowx 2006; Amin et al. 2008). The asymptotic length (L) varied between 52.0 and 61.5 cm and the K varied between 0.6 and 1.1 year^{-1}, but the present findings (L = 58.7 cm TL and K = 0.90 year^{-1}) are well within the range of previously published values (Table 4). Another test is the Munro's phi prime test (Munro and Pauly 1983; Pauly and Munro 1984), which is estimated from the length-frequency data ($\varphi' = 3.50$), and values were also found to be well within those for clupeid fishes (Munro and Pauly 1983; Pauly and Munro 1984). This indicates the estimated parameters are reliable, and this is the first time length-frequency data were collected from fish in all major habitat types by using digital imaging measurements. Nonetheless, sexually differentiated length-

TABLE 4. Comparative growth and population parameters of Hilsa in Bangladesh waters in different years.

Parameters	1995[a]	1996[b]	1997[c]	1998[c]	1999[c]	2002[d]	2003[e]	2016[f]
Asymptotic length (L_∞, cm)	58.3	59.97	61.50	66.00	60.00	53.70	53.55	58.70
Growth constant (K, year^{-1})	0.74	0.99	0.83	0.67	0.82	0.86	0.61	0.90
Growth performance index (φ)	3.40	3.55	3.50	3.46	3.47	3.40	3.24	3.50
Natural mortality (M, year^{-1})	1.18	1.41	1.28	1.25	1.28	1.36	1.10	1.36
Fishing mortality (F, year^{-1})	1.43	1.78	2.01	2.18	2.49	2.16	1.73	2.83
Total mortality (Z, year^{-1})	2.61	3.19	3.29	3.43	3.77	3.51	2.83	4.19
Sample number (n)	9,318	8,692	6,123	6,189	10,922	15,788	20,301	16,908

[a]After Rahman et al. (1998).
[b]After Rahman et al. (1999).
[c]After Amin et al. (2004).
[d]After Haldar and Amin (2005).
[e]After Amin et al. (2008).
[f]Present study.

frequency data could provide more reliable information, and this area should receive further investigation.

The values of the growth performance index (φ) had low variability and were within the range of those for clupeid species (Munro and Pauly 1983). Natural mortality also had a low variability (1.10–1.41 year^{-1}), which means that there was no remarkable adverse environmental impact on the fishery of Hilsa in the investigated area, and is similar to the values estimated by others (Miah et al. 1998; Rahman et al. 2000; Rahman and Cowx 2006; Amin et al. 2008). However, fishing mortality varied widely from 0.43 to 2.49 year^{-1} and had a mean of 2.43 year^{-1}, which was remarkably higher than the findings by other researchers in the area. This was supported by indications that the Hilsa fisheries are overexploited at a rate of 0.67, which exceeds the optimum of 0.50 by 0.17 (or 17%). This could be due to some fishers violating the 22-d brood-catch ban period and/or fishing in sanctuary areas. This elevated E value was not always the case, as values were around 0.55 in the mid-1990s but then gradually began to increase to 0.66 by 1999 (Amin et al. 2004). This level of exploitation remained steady at 0.66 (Rahman et al. 1999) and presently is at 0.60 (Rahman et al. 2000).

Although it is not possible to increase the catch yield without increasing the exploitation level, the fishery should be maintained at a biologically optimum level of exploitation to prevent a fisheries collapse. However, this raises questions how this could be achieved. Perhaps the most obvious answer might be to regulate fishing pressure by reducing the amount of fishing effort or reducing the number of fish caught using the same effort. For this to be effective in a large exploited fishery, a sound management plan linked to the socio-economic conditions of the fishing communities as well as environmental sustainability would be necessary (Rahman and Cowx 2008). This is problematic because this fishery encompasses a wide range of habitats that include marine, estuaries, and rivers and over 52,000 artisanal boats that are important for the livelihood of half a million people that depend on Hilsa catches (DOF 2016). Consequently, a sustainable management plan for the Hilsa fishery has to be formulated and properly implemented.

The recruitment pattern for the Hilsa population was more or less continuous with two major pulses separated by two normal curves, which was similar to patterns observed by others (Rahman 2001; Rahman and Cowx 2008). However, a third pulse that consisted of 2 months was also observed just after the peak pulse. Considering the spawning seasons of the fish, it may be possible that the first, second, and third recruitment pulses could be due to offspring from early spawners (August), peak spawners (September–October) and late spawners (January–February), respectively (Rahman 2007). Nevertheless, management measures should focus on the peak pulse that corresponds to the peak spawners of September–October, because this is when Hilsa spawn in huge numbers within a short period of time.

Steady State Biomass and Maximum Sustainable Yield

The estimated SSB and the population number showed a close association with fish size (Table 3). However, possibly due to the high fishing pressure, the number of the larger-sized fish was remarkably reduced, and no significant contribution was obtained from fish larger than 44 cm TL (Table 3). This should be viewed as a warning sign in terms of maintaining a sustainable Hilsa fisheries, and increased efforts should be made to protect Hilsa broodfish. In fact, due to the intense protection of broodstock Hilsa in recent years, larger-sized Hilsa (>1 kg and >42 cm TL) reappeared in significant numbers by about 15% on average from 2015 to 2016 in Bangladesh waters (Wahab 2016).

The estimated MSY of 526,000 metric tons was much higher than the Hilsa catch of that period (387,000 metric tons), indicating the potential benefit of achieving the MSY through maintaining a recommended length at first capture (L_c of 27 cm TL). The previously estimated MSY values were 162,396 metric tons (Amin et al. 2002), 235,130 metric tons (Haldar and Amin 2005), and 210,125 metric tons (Amin et al. 2008), which showed two patterns: a gradual increasing trend in MSY with few fluctuations during 2002 and 2008, and an MSY lower than that determined in the present study. This may be due to increased survival through some improvements to the protection of juveniles and broodfish.

Management Issues and Options

The three main outputs in this study that would be important for sustainable Hilsa management in Bangladesh are the MSY, the exploitation level E, and the recommended L_c. To obtain the estimated MSY, it is essential that the recommended L_c of 27 cm TL is followed, which may be achieved by placing regulations on the allowable mesh size. The optimum mesh size to catch Hilsa of 27 cm TL is 6.5 cm, based on the gill-net selectivity study for this species by Rahman and Cowx (2008). Currently, the banned Hilsa size is >25 cm TL, and if maintained this would have an expected yield of 490,000 metric tons, which is similar to the MSY. However, the current ban on the gill-net mesh size is >4.5 cm, which would catch Hilsa smaller than 25 cm TL. Therefore, it is recommended that any gill-net mesh size smaller than 6.5 cm that uses normal nylon twine should be prohibited for harvesting Hilsa. Another important issue is maintaining the optimum exploitation level of 0.5, which is lower than the value of 0.67 obtained in this study. Again, this may also be achieved by implementing new gill-net mesh sizes to allow juveniles to achieve a size of at least 27 cm TL at first capture. In addition, this would increase the chances for fish to spawn as well as achieve a higher biomass for each fish taken.

Some of these measures have already been effectively put into practice in Bangladesh (Islam et al. 2016b, 2017). Some recent studies assessing the effectiveness of the incentive-based Hilsa fishery management in Bangladesh suggest some improvements in reducing the capture of small-sized fish as well as protecting the Hilsa broodfish during the peak spawning season (Mohammed 2013; Bladon et al. 2016; Dewhurst-Richman et al. 2016; Islam et al. 2016a; Wahab 2016). Since the adoption of the Hilsa Fisheries Management Action Plan (HFMAP) by the Bangladesh Department of Fisheries in 2003, fisheries management has moved from a strict regulatory regime to an approach that combines regulations with direct economic “carrot-and-stick” incentives that compensate fishing households affected by seasonal Hilsa fishing bans (Mohammed and Wahab 2013). This incentive-based conservation activity has been hailed as one of the most cost-effective and efficient ways to manage natural resources (Haldar and Ali 2014). This is fully funded by the Bangladesh government through a pre-existing Vulnerable Group Feeding (VGF) program and currently provides over 200,000 affected households with 40 kg of rice per month from February to May each year. Another economic incentive mechanism, payments for ecosystem services (PES), has been implemented by rewarding resource users for improved practices (Tacconi 2012; Lau 2013; Porrasa et al. 2017). Alternative income-generating activities (AIGAs) and livelihood diversification may add further value. Effective community surveillance including representatives from all stakeholders would be instrumental to ensure compliance with conservation rules and regulations. An effective, sanctuary-based, comanagement body should be introduced in all the sanctuaries to conserve resources in a sustainable manner (Islam et al. 2018; van Brakel et al. 2018). However, because Hilsa is a shared species in the Bay of Bengal region, especially in Bangladesh, India, and Myanmar, a regional management initiative, in addition to the national efforts, could be initiated to further improve the management of the species.

Based on the output of the present study along with other management strategies described above, we believe that a holistic approach is needed that takes into consideration various socio-ecological issues. This will be essential to preserve Hilsa as a highly commercially important species for the livelihood of the Bangladeshi population, as well as to the people of other regional countries.

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