Evolution of wetlands in lower reaches of Bagmari–Bansloi–Pagla rivers: a study using multidated images and maps

Debabrata Mondal[1,2,*] and Swades Pal[2]

[1]Department of Geography, Subhas Chandra Bose Centenary College, P.O. Murshidabad, Murshidabad 742 149, India
[2]Department of Geography, University of Gour Banga, P. O. English Bazar, Malda 732 103, India

Numerous seasonally flooded wetlands in the lower Gangetic floodplain offer unique natural habitat for many migratory bird species due to their geographical location and hydro-ecological functioning. The various developmental projects change the riverine flow regime and cause hydro-ecological modification in the Gangetic floodplain wetland system. This study presents a comprehensive spatio-temporal monitoring of wetland dynamics in the lower segment of the Bagmari–Bansloi–Pagla sub-basin of the Ganga–Bhagirathi rivers using image classification technique and some fragmentation indices. Our results reveal that the land-use conversion and fragmentation processes that affect the wetland landscape are generally represented as the evolution, and consecutive drying and squeezing of wetland patches over the study area. The water-spreading area of the wetlands was highest during 1975 after the construction of the Bhagirathi feeder canal. The situation has worsened since 1980 due to cumulative effects of agriculture after the Green revolution, and the whole landscape has become a fragmented, isolated and agronomically managed wetland.

Keywords: Ahiran wetland, fragmentation, green revolution, hydrological alteration, landsat image.

THE seasonally flooded wetlands in developing countries are mistreated due to their ephemeral and erratic appearance and small size; however, their significance is comparable to the more permanent wetlands[1,2]. The Ramsar Conservation on Wetlands[2] has grouped such wetlands as a subset of the 'temporary pool' and nominated them for inclusion in the directory of wetlands of global importance. Generally, wetlands are fragile ecotone between terrestrial and aquatic habitats and they play a pivotal role in the landscape by providing beneficial natural resources to human civilizations[3]. Wetlands cover almost 10% of the earth's land surface and 15% of this is floodplains[4]. About 50% of the world's wetlands have been lost since 1990 (refs 5, 6) due to anthropogenic causes like urbanization, agricultural expansion, and water system regulation and various developmental activities. Foote *et al.*[7] and Prasad *et al.*[8] have identified different processes of wetland loss in India under two broad groups. Acute losses, which act usually over a short period, and chronic losses that occur over several years[7]. Scott and Pole[9] documented that about 45% of Indian wetlands is moderate to highly threatened. In this subtropical region, the floodplain wetlands are almost lost due to direct and indirect alterations of hydrological regimes[10]. Wetlands in the Gangetic floodplain are being rapidly converted due to agricultural encroachment and draining for irrigation[11], although their natural occurrence may yield 2.75 times greater economic value than agriculturally converted wetlands[12].

Floodplain wetlands are among the most threatened habitat[4,8,13] and they are susceptible to deluging once or more in a year. Junk *et al.*[14] defined the floodplain as an 'aquatic/terrestrial transition zone' (ATTZ) that has unique properties in terms of its hydrology and biota. Floodplains also offer a suitable environment for human settlements through their direct and indirect effects on crop production. In the last few decades, however, the rapid growth of population and enhanced demand for water forced the human population to manage watershed and hydrological alteration. Construction of large barrages and associated irrigational canals also alter the hydrological set-up and can change the forms and functions of wetlands. Many researchers have studied the issues of hydrological alteration in floodplain system caused by various development activities, viz. construction of large dams, barrages, canals and policy implementation of the green revolution, etc. The impacts of hydrological alteration on floodplain habitat caused by dams have been studied[15–17]. The general effects of hydrological alteration on wetland systems caused by irrigation canals were reported by Rao[18] and Behera *et al.*[19]. To assess the changes in wetland landscape, satellite remote sensing data can provide a consistent and repeatable measurement of landscape condition and permit monitoring the slow or sudden changes in land surface condition[20].

In India about 58.2 m ha area is occupied by wetlands, including those under wet paddy cultivation[21], greater parts of which depend directly or indirectly on major

*For correspondence. (e-mail: mandal23dev@gmail.com)

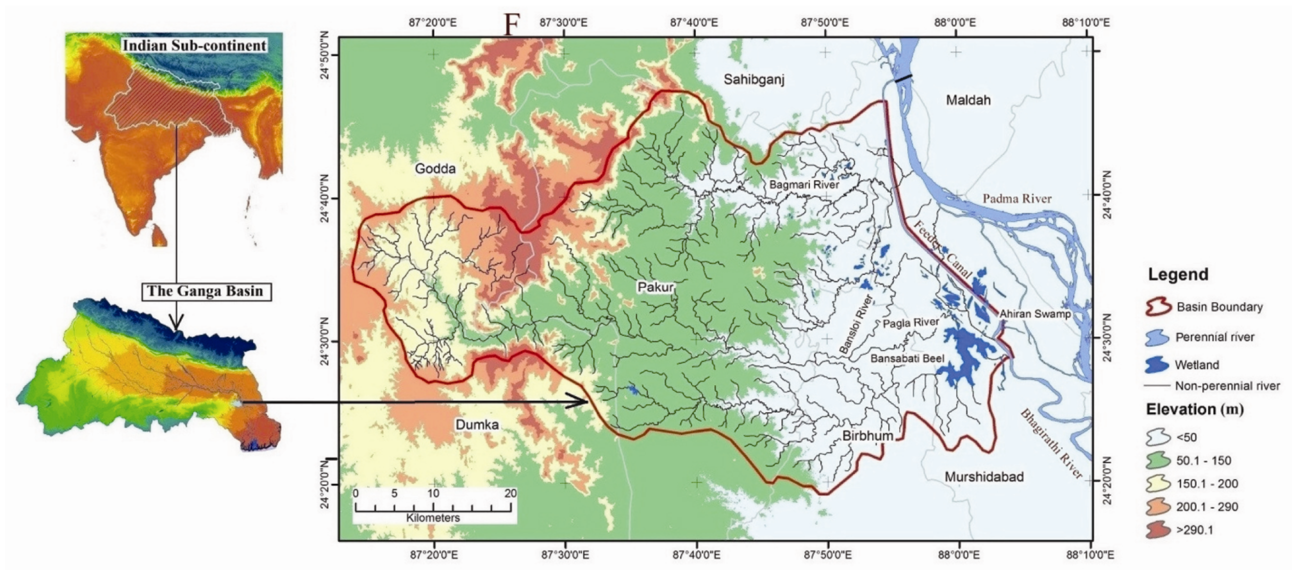

Figure 1. Location map of the Bagmari–Bansloi–Pagla river basin including major wetlands.

(rivers like the Ganga, Brahmaputra, Narmada, Godavari, Krishna, Kaveri and Tapti[8]. Here majority of the wetlands appear as maximum water spread area during deluging period of the monsoon (June to September) and disappear in the dry season[10]. This indicates the strong footprint of monsoon in the hydrology of wetlands[22]. Wetlands in the lower Gangetic floodplain play a pivotal role due to their hydro-ecological functions and economic value and livelihood for 21% of the marginalized section of the population[12]. According to a report of the Space Applications Centre[23], in the Gangetic West Bengal, there are 1489 oxbow lakes, 167 wetlands with size greater than 50 ha, 7065 wetlands with size greater than 2.25 ha and 56,313 wetlands with size less than 2.25 ha covering an area of 504,306.56 ha. West Bengal holds the second position in terms of riverine wetlands[22]. The floodplain wetlands in West Bengal periodically become a part of the Ganga River[24], whereas only discrete wetlands are recognized as lakes, pond and oxbow lakes[25].

In the present study, we have utilized remote sensing and geographic information system to acquire the land use and spatial statistics of wetlands at the landscape level. The primary objective of this study is to capture the evolution processes of wetlands in the lower segment of the Bagmari–Bansloi–Pagla river basin after completion of the Farakka barrage projects and later the growing intensive agricultural practice.

Materials and methods

Study area

The Bagmari–Bansloi–Pagla basin, a sub-basin of the Bhagirathi river is located between 24°19–24°47′N and 87°14′–88°04′E covering an area of 2522 sq. km (Figure 1). It comprises part of Birbhum and Murshidabad districts of West Bengal, and Pakur, Gadda and Dumka districts of Jharkhand. The entire catchment area is drained by three major non-perennial rivers, namely the Bagmari, Pagla and Bansloi, originating from the Rajmahal hills and running eastward and finally debouched into the Padma and Bhagirathi rivers. Construction of feeder canal has partly detached its natural connection from the Padma River, thus it playing a new confluence of few rivers coming from Rajmahal hills.

Topographically the lower segment of the Bagmari–Bansloi–Pagla basin is part of the lowland floodplains of the Ganga–Bhagirathi river system, also known as the Moribund delta[26] characterized by the presence of numerous inter-distributary swamps and meander cut-offs[27]. The presence of a near-surface groundwater level and flat topography are the conjunctive effect for the occurrence of wetlands in this region[28]. Many small and large wetlands locally called 'Beel', either permanent or temporal, have been categorized as marshy lowlands with numerous freshwater swamps. All of these are nourished by monsoon rainfall, and seepage from the Bhagirathi feeder canal emanating from the River Ganga from the Farakka barrage. Few of them are interconnected by small streams and encircled by wetland shrubs and few patches of marsh serve as a suitable habitat for migratory birds during the winter season.

Ahiran beel (Ahiron), Baghar beel (Bansabati beel), Chander beel, etc. are important wetlands and they occupy majority of the landscape in the study site. The Ahiran beel comprising an area of ~400 ha was identified in the list of important bird sanctuaries during 2005–06 under the National Wetland Conservation Programme (NWCP) by the Ministry of Environment and Forests (MoEF), Government of India (GoI). Migratory bird populations along with some native migratory (Figure 2) and resident birds (Table 1) use this wetland as a breeding ground during the winter period. It is situated near Jangipur Railway station, 35 km south from the Farakka barrage and also adjacent to the National Highway 34. Bansabati beel, also known as Baghar beel, is much larger than Ahiron, where 4000 coots along with more than 1000+ pintails and red crested pochards, and few white necked storks were found in 1998 (ref. 29).

Technique related to remote sensing

For monitoring of wetland dynamics, we acquired eight scenes of Landsat data (Level 1 Terrain Corrected (L1T) product; Table 2) from the US Geological Survey (USGS) Global Visualization Viewer that were pre-geo referenced to UTM zone 45 North projection using WGS-84 datum. All images were collected between November and February to clearly delineate the wetlands. The images were radiometrically corrected and nearest neighbour algorithm was used to resample them into 30 m output pixels.

At the stage of first water discharge (21 April 1975) from the Farakka barrage to the Bhagirathi feeder canal, water-spreading areas over the wetlands reached the maximum. We collected one MSS image (18 November 1975) during this period, and wetland polygons were derived by visual classification and onscreen digitization from the image. In order to carry out the temporal land-cover dynamics, subsets of imagery were taken. Then we separately analysed wetland land-cover dynamics in different time periods. For meaningful classification, we used four bands of MSS images and equivalent three bands (B2, B3 and B4) of TM images. The spectral wavelength range of MSS data is similar to the three bands of TM data[15]. The Iterative Self-Organizing Data Analysis (ISODATA) clustering algorithm of ERDAS Imagine (v. 9.0) software was used to identify spectrally similar pixels[15], as they provide the most comprehensive information on the spectral characteristics of an area[6]. Sixteen clusters were specified for the ISODATA clustering and 16 land-cover types were identified in the primary classification procedure. Based on ancillary information and knowledge of the study area, the cluster information was merged into five broad groups, including (i) open water, (ii) marsh, (iii) shrub, (iv) paddy field and (v) fallow

Figure 2. Ahiran wetland in the lower reaches of Bagmari–Bansloi–Pagla river showing the habitat of Red crested pochard.

Table 1. List of bird species observed in the study area

Order:	Pelecaniformes
Family:	Phalacrocoracidae
Large cormorant	*Phalacrocorax carbo*
Indian shag/pan-kawri	*Phalacrocorax fuscicollis*
Little cormorant	*Phalacrocorax niger*
Darter	*Anhingrarufa melanogaster* Pennant
Order:	Ciconiiformes
Family:	Ardeidae
Grey heron	*Ardeacinerea*
Indian pond heron	*Ardeola grayii*
Small or median egret	*Egretta intermedia*
Little egret	*Egretta garzetta*
Night heron	*Nycticorax nycticorax*
Yellow bittern	*Ixobrychus sinensis*
Family:	Ciconiidae
White-necked Stork	*Ciconia episcopus*
Lesser adjutant	*Leptoptilos javanicus*
Order:	Anseriformes
Family:	Anatidae
Barheaded goose	*Anser indicus*
Larger whistling teal	*Dendrocygna bicolor*
Brahminy duck	*Tadorna ferruginea*
Pintail	*Anas acuta*
Gadwal	*Anas strepera strepera*
Garganey	*Anas querquedula*
Shoveller	*Anas clypeata*
Red crested pochard	*Netta rufina*
Common pochard	*Aythya ferina*
Cotton teal	*Nettapus coromandelianus*
Comb duck	*Sarkidiornis melanotos*
Family:	Rallidae
Coot	*Fulica atra atra*
Indian purple moorhen	*Porphyrio porphyrio poliocephalus*
Order:	Charadriiformes
Family	Jacanidae
Pheasant-tailed jacana	*Hydrophasianus chirurgus*
Bronzewinged jacana	*Metopidius indicus*
Order:	Charadriiformes
Family:	Charadriidae
SubFamily:	Charadriinae
European little ringed plover	*Charadrius dubius curonicus*
SubFamily :	Scolopacinae
Whimbrel	*Numenius phaeopus phaeopus*
Curlew	*Numenius arquata arquata*
Common redshank	*Tringa totanust*
Greenshank	*Tringa nebularia*
Common sandpiper	*Tringa hypoleucos*
Family:	Burhinidae
Stone curlew	*Burhinusoedicnemus*

Source: ref. 44.

Table 2. Summary of Landsat MSS, TM and OLI imageries

Satellite	Sensor	Bands used	Spatial resolution (m)	Path/row	Date of acquisition
Landsat 8	OLI	G, R, NIR	30	139/43	20.11.2013
Landsat 5	TM	G, R, NIR	30	139/43	17.11.2006
Landsat 7	ETM+	G, R, NIR	30	139/43	10.12.2000
Landsat 5	TM	G, R, NIR	28.5	139/43	21.11.1990
Landsat 2	MSS	G, R, NIR, MIR	57	149/43	10.02.1977
Landsat 2	MSS	G, R, MIR*	60	149/43	18.11.1975
Landsat 2	MSS	G, R, MIR*	60	149/43	21.02.1975
Landsat 1	MSS	G, R, NIR, MIR	60	149/43	17.01.1973

*Landsat look images with geographic reference 'natural colour'.

Table 3. List of spatial metrics used in the study

Metric	Description	Formula		Range
Total area (CA)	Total area of patches in the class level	$CA = \sum_{j=1}^{m} a_{ij}(1/10,000)$	CA equals the sum of the areas (m^2) of all patches of the corresponding patch type, divided by 10,000 (to convert to hectares); that is, total class area.	CA > 0, without limit.
Patch density (PD)	Abundance of patch type.	$PD = n_i/A(10,000)(100)$	n_i is the total number of patches in the landscape of patch type (class) i. A is the total landscape area (m^2).	$P > 0$, constrained by cell size.
Number of patches (NP)	Total number of patches in the class level	$NP = n_i$	n_i is the number of patches in the landscape of patch type (class) i.	NP ≥ 1, without limit.
Splitting index (SPLIT)	Split is based on the cumulative patch area distribution and is interpreted as the effective mesh number.	$SPLIT = A^2/\sum_{j=1}^{n} a_{ij}^2$	a_{ij} is the area (m^2) of patch ij; A is the total landscape area (m^2).	1 < SPLIT ≤ number of cells in the landscape area squared.
Largest patch index (LPI)	Largest patch index at the class level quantifies the percentage of total landscape area comprised by the largest patch.	$LPI = (\max_{j=1}^{n}(a_{ij})/A)(100)$	a_{ij} is the area (m^2) of patch ij; A is the total landscape area (m^2).	0 < LPI ≤ 100.

Adopted from McGarigal *et al.*[32].

area. The final classified maps were verified using various ancillary data.

Some index-oriented image classification techniques, viz. normalized difference water index (NDWI) and normalized difference vegetation index (NDVI) were also used to identify the qualitative changes in wetland water and vegetation. NDVI is calculated using equations[30]

$$NDVI = NIR - R/NIR + R. \quad (1)$$

NDWI is calculated using the following equation[31]

$$NDWI = Green - NIR/Green + NIR, \quad (2)$$

where NIR, R and Green are the near infrared, red and green bands of the MSS, TM, ETM+ and OLI sensors respectively.

Technique relating to spatial statistics

In order to carry out spatial statistics, e.g. fragmentation statistics, wetland centroids, etc., we combined three land-cover classes, i.e. open water, marsh and wetland shrub into 'wetland' class and the others into 'non-wetland' class. The extracted wetland area was processed using FRAGSTAT©4.1 software[32]. Five class level metrics were used to indicate the wetland fragmentation (Table 3).

We studied the spatial changes of wetland centroids from 1973 to 2013 using the equations[17]

$$X_t = \sum_{i=1}^{N_t} (A_{it} \times x_{it})/A_t,$$

$$Y_t = \sum_{i=1}^{N_t} (A_{it} \times y_{it})/A_t,$$

Table 4. Dynamics of land cover, vegetation and water index

Year	Areal (ha) and relative (%, in parentheses) land cover								
	Open water	Marsh	Wetland shrub	Wetland agriculture	Fallow land	NDVI maximum	NDVI minimum	NDWI maximum	NDWI minimum
17 January 1973	2408.8 (36.74)	242.10 (3.69)	354.04 (5.38)	450.20 (6.88)	3102.04 (47.31)	0.461	–0.664	0.455	–0.581
18 November 1975	6557.04	–	–	–	–	–	–	–	–
10 February 1977	4012.69 (61.20)	673.51 (10.27)	1100.12 (16.78)	745.71 (11.37)	25.01 (0.38)	0.518	–0.575	0.926	–0.850
21 November 1990	2821.43 (43.03)	582.02 (8.88)	2004.29 (30.57)	1087.28 (16.58)	62.02 (0.95)	0.686	–0.802	0.838	–0.606
10 December 2000	1809.72 (27.60)	51.21 (0.78)	2185.92 (33.34)	2458.62 (37.50)	51.57 (0.79)	0.714	–0.361	0.401	–0.247
17 November 2006	773.19 (11.79)	254.88 (3.89)	1293.42 (19.73)	2611.14 (39.82)	1624.41 (24.77)	0.574	–0.333	0.322	–0.513
20 November 2013	452.7 (6.90)	382.77 (5.84)	1240.56 (18.92)	2825.82 (43.10)	1655.19 (25.24)	0.463	–0.254	0.279	–0.411

where X_t and Y_t are the coordinates of centroid points of the wetlands at time t. A_{it} the area of the ith patch at time t, x_{it} and y_{it} the coordinates of the ith patch at time t and N_t is the total number of patches at time t.

Accuracy assessment

To assist the validation process, we adopted a number of strategies and used different types of ancillary information. The classification accuracy of land-cover products was a challenging task in the absence of ancillary data. Due to the deficiency of coinciding past aerial photographs or higher resolution satellite data, we constrained this validation to other types of ancillary information. To validate classified land-cover maps older than 1990, we used Survey of India (SOI) topographic map of 1970 at 1 : 50,000 scale and Cadastral map of 1976–77 (1 : 3960 scale) made under the West Bengal Estate Acquisition Act, 1953 on the basis of Land Reform (LR) survey. An image from Google Earth was printed on A1-size paper with few Cadastral maps taken to the field. These hard-copy maps were used to identify the location of plots (smaller units in the Cadastral map) on the ground and then reference points were recorded using handheld GPS receiver. Key informants, i.e. aged rural people and local Amin (trained and registered surveyors) were consulted to collect previous land-cover pattern of the selected plot as reference sites of 1973 and 1977. The ancillary plot-level land-cover information for the Government owned plots was also collected from Land and Land Reform Department, Government of West Bengal. To define the accuracy we used SOI topographic map (surveyed 1990–91) coinciding with Landsat TM image (November 1990). The IRS-ID panchromatic image (5.8 m) was used as reference data for the 2000 land-cover map. We collected sample points of each land-cover class from historical Google Earth image and field survey for the 2006 and 2013 maps.

Results

Validation

The results were derived from error matrix and kappa statistics, which are used to express the proportionate error generated by a classification process relative to that of completely random classification[33]. We found that overall accuracies for MSS were 84.2% and 83.4% with corresponding kappa statistics of 77.7% and 76.2% respectively. The overall accuracies for land-cover maps of 1990, 2000, 2006 and 2013 were 85.4%, 86.8%, 85.1% and 90.6% with corresponding kappa statistics of 79.5%, 80.5%, 79.2% and 84.9% respectively.

Land-cover changes and dynamics of vegetation and water index

The results revealed that the land-cover statistics, and NDVI and NDWI of the wetlands in the study area decreased each year during 1977–2000. Table 4 shows changes in the wetland area from 1977 to 2013, where total area of wetlands was 6557.04 ha in 1975. In 1977, maximum values of NDWI and NDVI were 0.518 and 0.926 respectively, and total 6557 ha area was divided into various patches, among which wetland shrubs occurred in an area of 1100 ha.

About 745 ha area turned into wetland agricultural area, while marsh grew in an area of 673 ha. Also, a small portion (25 ha) had turned into fallow land. In 1990, open water further reduced to almost 75% and subsequently other patches increased, except marsh which decreased to 582 ha. There were no noticeable changes in the maximum value of NDWI as well as NDVI. Again in 2000, open water and fallow land decreased, while wetland shrub and agriculture land increased to some extent. However, marsh shrunk unpredictably to 51 ha. Also maximum values of NDWI and NDVI dropped suddenly to almost half of their previous values. In 2006 area under open water shrunk to less than half its value and wetland shrub also decreased. However, fallow land increased drastically and covered an area of 624 ha. Marsh increased significantly, but area under wetland agriculture remained almost the same. The maximum value of NDWI increased, but that of NDVI decreased. Finally, from the index values of 2013, it is apparent that wetland agriculture gradually became the dominating patch covering an area of 2825 ha and open water, which had dominated the whole area of 6557 ha in 1975, shrunk to 452 ha. Maximum values of NDWI and NDVI decreased overall from 1977 to 2013.

Dynamics of fragmentation indices

Satellite imagery showed that the total area of wetlands in the study region was 3005.65 ha in 1973, but it increased dramatically to 6557 ha in 1975. Although there was a slight increase in the number of patches from 48 to 69, and in patch density from 0.052 to 0.0748 during that interval, the split index decreased sharply from 15,374.92 to 386.80. Also, the largest patch index (LPI) increased abruptly from 0.569 to 5.0654. However, from 1975, the total area and LPI started to reduce gradually while the fragmentation indices increased overall. In 1977, the total area reduced to 5786.32 ha and LPI fell to 2.691, almost half the value in 1975. Also, patch density and number of patches decreased to 0.0455 and 42 respectively. Splitting index increased to 1206.257 in just two years (1975 to 1977). Again, in 1990, total area and LPI reduced to 5407.74 ha and 2.3087 respectively. On the other hand, number of patches, patch density and splitting index rose to 79, 0.0856 and 1788.01 respectively. In 2000, total area and LPI further decreased to 4046.85 ha and 1.2011 respectively, while the number of patches and patch density increased slightly to 83 and 0.0899 respectively, and split index increased to 6557.04. In 2006, there was a considerable drop from 4046.85 to 2321.49 ha in total area and from 1.2011 to 1.0661 in LPI. The number of patches, patch density and splitting index increased to 113, 0.1225 and 7958.394 respectively. In 2013, total area, patch number and patch density reduced sharply to 2076.03 ha, 72 and 0.078 respectively, where splitting index decreased slightly to 7933.89. However, there was a slight rise in LPI from 1.0661 to 1.0986 in seven years (2006–2013).

Dynamics of wetland centroid

From 1973 to 1975, the centroid of wetlands displaced 4.58 km to the southeast, and then from 1975 to 1977 it further moved 3.10 km in the same direction. However, from 1977 to 1990, the movement of the centroid reversed to the northwest, with a shift distance of 1.599 km. From 1990 to 2000, it further shifted 725 m to the north. Again from 2000 to 2006, it displaced 2.15 km to the northwest, but from 2006 to 2013 it moved 2.26 km back southeast. From Figure 3, it is clear that the wetland area moved away to the southwest.

The above results clearly revealed the two phases in the dynamics of the wetlands, i.e. an unusual increase in size from 1973 to 1975, and gradual fragmentation and depletion thereafter. The driving forces behind the wetland dynamics in this study area include: (i) construction of feeder canal (Figure 4) which increased the water-spreading area during 1973–75, and (ii) anthropogenic as well as natural factors, viz. agricultural expansion, groundwater withdrawal, damaging of outlets systems caused by National Highway 34, railway line and resultant siltation which has caused wetland fragmentation since 1975.

The feeder canal on the right side of the study area was constructed during the Farakka barrage project proposed in 1962. Before this project, River Bhagirathi, separated from the Ganga near Mithipurat, northern part of Murshidabad district, West Bengal was fed by some other tributaries like Pagla, Bansloi, Mayurakshi, Ajoy, Damodar, etc. However, gradual siltation at the bifurcation point reduced the flow of freshwater into the Bhagirathi and consequently, this reduced freshwater discharge to the southern part of the river, which in turn threatened the navigability of the Kolkata Port[34]. Therefore, a barrage was constructed across the Ganga at Farakka to maintain water flow at Kolkata Port and to improve the communication facility between north and south Bengal. A 38 km long feeder canal was excavated to divert 40,000 cusecs

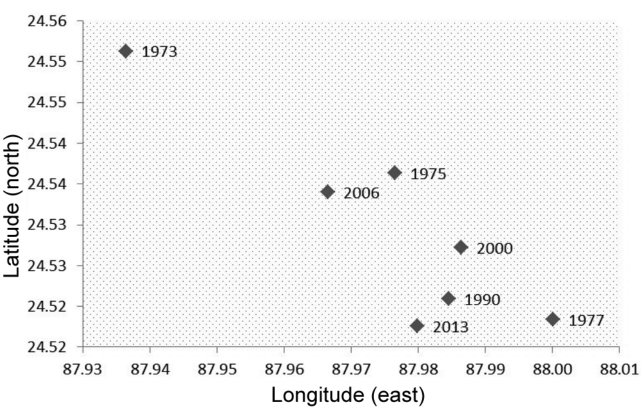

Figure 3. Location of wetland centroid points in the study area from 1973 to 2013.

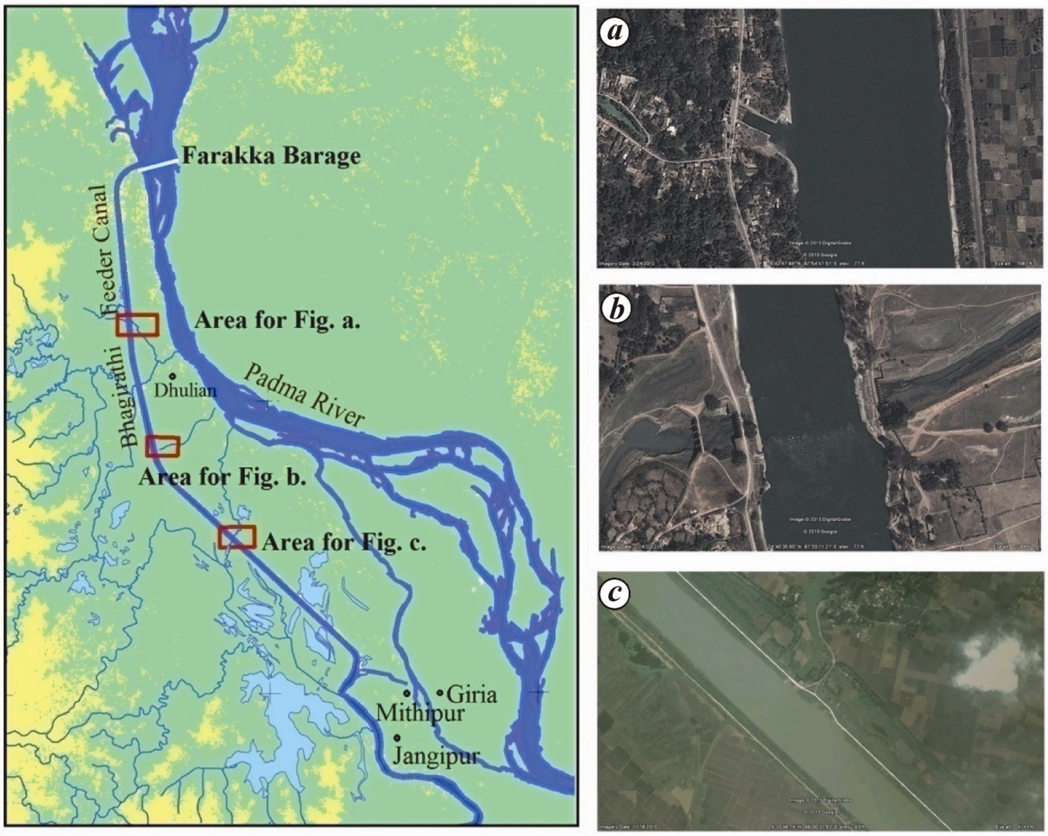

Figure 4. Map showing location of Farakka barrage, Bhagirathi feeder canal: ***a***, Canal inlet; ***b***, Bagmari syphon; ***c***, regulator.

Table 5. Calculated values of landscape metrics in different years

Year	Total area (CA)	Number of patches (NP)	Patch density (PD)	Largest patch index (LPI)	Split index (SPLIT)
17 January 1973	3005.65	48	0.052	0.569	15374.92
18 November 1975	6557.04	69	0.0748	5.0654	386.8
10 February 1977	5786.32	42	0.0455	2.6912	1206.25
21 November 1990	5407.74	79	0.0856	2.3087	1788.01
10 December 2000	4046.85	83	0.0899	1.2011	6394.9
17 November 2006	2321.49	113	0.1225	1.0661	7958.39
20 November 2013	2076.03	72	0.078	1.0986	7933.89

of water directly to the Bhagirathi and they meet near Jangipur in Murshidabad district. On 21 April 1975, water began to be released from the Ganga into the Bhagirathi through this canal. The digging of Bhagirathi feeder canal and associated national highway (NH 34) and railway line construction hindered the natural flow of the rivers. Practically an estimated 6557 ha area (Table 5) started to experience the swampy conditions. This sudden increase of wetlands was noticeable due to leaching of water from the canal and due to obstruction of basin outlet. The rise of groundwater level after the release of water through the canal initially supported water stagnation over the study area. Although one syphon (Bagmari syphon; Figure 4 *b*) drainage regulators and inlets (Figure 4 *a* and *c*) were built to overcome this situation, they were not sufficient for draining the water. Eventually, leaching of water started logging at the right side of the canal for few years (Figure 5). In a detailed description of the 2000 floods in Bengal, Chapman and Rudra[35] wrote, '… the canal cuts across the drainage outlets of four small rivers coming from the hills of Chotanagpur in adjacent Jharkhand state – the Trimohoni, Kanloi, Bagmari, and Madhabjani. Before the canal was built, these drained into the Ganges just upstream of its first distributary, the Bhagirathi. After the canal was built, they drained into it, thence into the Bhagirathi. In ordinary seasons their small

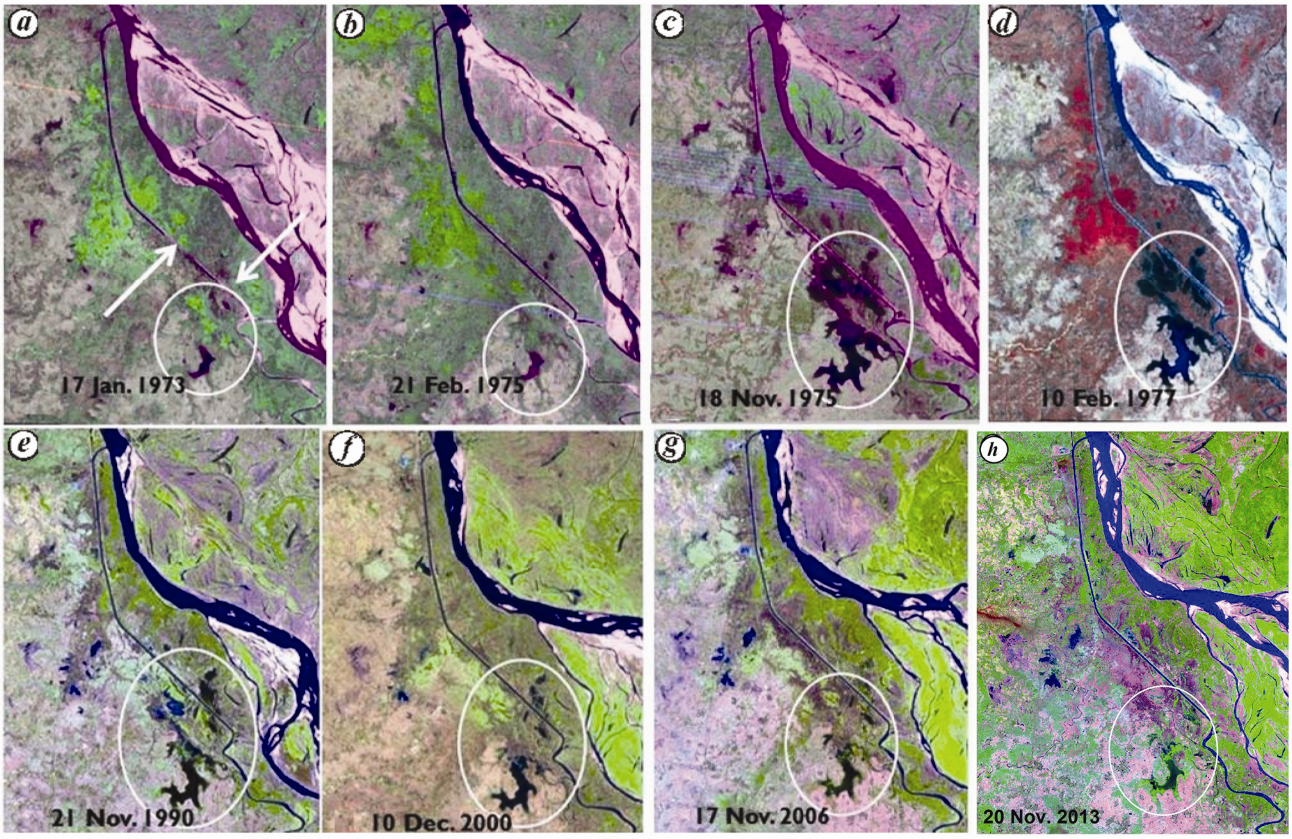

Figure 5. Episodic change in water spreading over the wetland landscape. ***a***, During construction period of the Feeder canal; ***b***, Before two months of water discharge; ***c***, After seven months of water discharge; ***d***, After two years of water discharge; ***e–h***, Drying of wetland after the green revolution.

contribution to discharge would be welcome, but there is no alternative escape for major influxes. Thus, the huge discharges from Jharkhand down these rivers in late September 2000 were ducted straight into the Bhagirathi. The blockage of the line of drainage has also turned much of the land on the west side of the canal into unusable swampland'.

The altered flow regime of river disrupts the dynamic equilibrium between inlet sediment accumulation and movement, modifies habitat dynamics also, forming different environment to which the native biota may be poorly adopted[36]. In the study area resulting impacts on the native biota are much more intense in the floodplain.

Agriculture is the major cause for wetland loss in Asia, where about 27% of wetlands has been drained for intensive agriculture[5,37]. The lower Gangetic floodplain is traditionally known as the rice-growing belt in West Bengal[38]. During the last several decades, rapid population growth and dramatic increase in food demand switched human dependence from surface water to groundwater[28].

Based on the land-cover analysis, the total area of open water and area under marsh dramatically reduced, while agriculture along with fallow land gradually increased. This can be attributed to the agricultural development during this period. In Bengal, the agricultural output, mainly boro paddy cultivation (during the non-monsoon season, e.g. February to May) was intensified sharply after the 1980s that unleashed the green revolution[39,40]. This period also witnessed a significant increase in groundwater lifting[41,42] and extensive use of chemical fertilizers and insecticides by rural farmers of West Bengal[43]. The rate of wetland destruction increased and farmers in the rural area chose the low-lying marsh as paddy field to augment rice production. Consequently, areas of wetland were converted into paddy fields. The results of this study demonstrated that dominance and fragmentation indices also gradually declined after 1975–77, indicating that significant areas of wetlands were segmented into small patches. The fertilizer run-off from upland as well as the agricultural land in the vicinity of the wetlands was considerably higher after 1980s which enhanced the nutrient loading to the wetlands and also helped in the formation and development of wetland shrubs and weeds in the eutrophic environment. The range of two indices, NDVI and NDWI varied with respect to time in association with fragmentation and land-use statistics. The introduction of boro paddy cultivation together with technological advances in tube wells and large-capacity pumping for crop irrigation lowered the water table quickly, which possibly caused water scarcity in the area[7,11]. The lower groundwater level failed to support water stagnation over the wetlands. Thus, it can be established that steady drop of groundwater levels, land-cover conversion along with associated eutrophication may be primarily responsible for the gradual filling of swamps (Figure 5) that ultimately reduced the effective water-spreading area and resulted in fragmentation. Silting over the wetlands was enhanced due to soil entrainment from the agricultural fields around the wetlands. The halting of natural flow of drainage outlet also enhanced deposition of silt in that area. Reclamation of agricultural plots elevating few patches of land within the wetlands by bringing soil from outside was a major factor for reducing the effective water-spreading area and fragmentation of wetland continuity.

The results also indicated that the centroids of all wetlands were relocated and moved away from feeder canal during the study period due to notable modification of hydrological regime of the wetland system. Currently, few detrimental factors are driving natural wetland systems towards terrestrial systems, ultimately making the wetlands fragmented and isolated from the inflow/outflow system. Some interconnected swamps and lakes have lost their connection with the main channels and became isolated for several months or even years. Thus the vast swampland turned into paddy dominated the artificial and fragile ecosystem.

Conclusion

The results of the present study showed that the feeder canal plays a significant role in altering the hydrological regime of the wetland system. Factors such as increased sedimentation from surrounding regions, agricultural expansion, eutrophication and lowering of groundwater level are major vectors for interruptive wetland regime and ensuing treats on them. If this trend continues, wetlands will soon be converted into dry land and wetland ecotonian ecosystem will be converted to terrestrial or paddy-dominated ecosystem. Some of the major reasons behind wetland conversion are mass illiteracy about the goods and services of wetland, lack of evidences of effective and productive uses of wetlands, high expectation of immediate monetary returns from wetlands, indifferent thinking of considering wetlands as wasteland, lack of proper Governmental policy implementation, etc. Conservation efforts across large landscapes in participation with local people are necessary to make these wetlands productive and retain their ecological settings. Productive returns alone can prevent the rapid replacement of wetlands by agriculture, and inspire people towards making wetlands more productive and sustainable.

1. Li, L., Vrieling, A., Skidmore, A., Wang, T., Muñoz, A. R. and Turak, E., Evaluation of MODIS spectral indices for monitoring hydrological dynamics of a small, seasonally-flooded wetland in Southern Spain. *Wetlands*, 2015, **35**(5), 851–864.
2. Ramsar Convention on Wetlands, Wetlands: water, life and culture. In Resolution VIII.33 Guidance for Identifying, Sustainably Managing, and Designating Temporary Pools as Wetlands of International, 2002; http://www.ramsar.org/sites/default/files/documents/pdf/res/key_res_viii_33_e.pdf
3. Reddy, K. R. and Gale, P. M., Wetland processes and water quality: a symposium overview. *J. Environ. Qual.*, 1994, **23**(5), 875–877.
4. Tockner, K., Bunn, S. E., Gordon, C., Naiman R. J., Quinn, G. P., Standord, J. A. and Polunin, N. V. C., Flood plains: critically threatened ecosystems. *Aquatic Ecosystem* (ed. Polunin, N. V. C.), Cambridge University Press, Cambridge, 2008, pp. 45–61.
5. Finlayson, C. M., Davidson, N. C. and Stevenson, N. J., Wetland inventory, assessment and monitoring: Practical techniques and identification of major issues: summary. In Proceedings of Workshop 4, 2nd International Conference on Wetlands and Development, Dakar, Senegal, 8–14 November 1998. Darwin: Supervising Scientist Report 161.
6. Jiang, P., Cheng, L., Li, M., Zhao, R. and Huang, Q., Analysis of landscape fragmentation processes and driving forces in wetlands in arid areas: a case study of the middle reaches of the Heihe River, China. *Ecol. Indicators*, 2014, **46**, 240–252.
7. Foote, L., Pandey, S. and Krogman, N. T., Processes of wetland loss in India. *Environ. Conserv.*, 1996, **23**(1), 45–54.
8. Prasad, S. N. *et al.*, Conservation of wetlands of India – a review. *Trop. Ecol.*, 2002, **43**(1), 173–186.
9. Scott, D. A. and Pole, C. M., *A Status Overview of Asian Wetlands. Asian Wetlands Bureau*, Kuala Lumpur, Malaysia, 1989, Publication No. 53.
10. Gopal, B., Future of wetlands in tropical and subtropical Asia, especially in the face of climate change. *Aquat. Sci.*, 2013, **75**(11), 39–61.
11. Pal, S. and Akoma, O. C., Water scarcity in wetland area within Kandi Block of West Bengal: a hydro-ecological assessment. *Ethiop. J. Environ. Stud. Manage.*, 2009, **2**(3), 1–12.
12. MEA (Millennium Ecosystem Assessment), *Ecosystems and Human Well-being: Biodiversity Synthesis*, World Resources Institute, Washington DC, 2005, p. 68.
13. Tockner, K. and Stanford, J. A., Riverine flood plains: present state and future trends. *Environ. Conserv.*, 2002, **29**(03), 308–330.
14. Junk, W., Bayley, P. B. and Sparks, R. E., The flood pulse concept in river–floodplain systems. *Can. J. Fish. Aquat. Sci.*, 1986, **106**, 110–127.
15. Kingsford, R. T. and Thomas, R. F., Use of satellite image analysis to track wetland loss on the Murrumbidgee River flood plain in arid Australia, 1975–1998. *Water Sci. Technol.*, 2002, **45**(11), 45–54.
16. Kingsford, R. T. and Thomas, R. F., Destruction of wetlands and waterbird populations by dams and irrigation on the Murrumbidgee River in arid Australia. *Environ. Manage.*, 2004, **34**(3), 383–396.
17. Zhao, R., Chen, Y., Zhou, H., Li, Y., Qian, Y. and Zhang, L., Assessment of wetland fragmentation in the Tarim River basin, western China. *Environ. Geol.*, 2009, **57**(2), 455–464.
18. Rao, K. L., *India's Water Wealth: Its Assessment, Uses and Projections*, Orient Longman, New Delhi, 1975.
19. Behera, M. D., Chitale, V. S., Shaw, A., Roy, P. S. and Murthy, M. S. R., Wetland monitoring, serves as an index of land cover change – a study in Samaspur Wetlands, Uttar Pradesh, India. *J. Indian Soc. Remote Sensing*, 2012, **40**(2), 287–297.
20. Kennedy, R. E., Townsend, P. A., Gross, J. E., Cohen, W. B., Bolstad, P., Wang, Y. Q. and Adams, P., Remote sensing change detection tools for natural resource managers: understanding concepts and trade-offs in the design of landscape monitoring projects. *Remote Sensing of Environ.*, 2009, **113**, 1382–1396.

21. Anon., Directory of Indian Wetlands WWFINDIA, New Delhi and AWB, Kuala Lumpur, 1993, pp xvi + 264, 32 maps.
22. Panigrahy, S., Murthy, T. V. R., Patel, J. G. and Singh, T. S., Wetlands of India: inventory and assessment at 1 : 50,000 scale using geospatial techniques. *Curr. Sci.*, 2013, **102**(6), 852–856.
23. Space Applications Centre, *National Wetland Atlas: West Bengal*, SAC/RESA/AFEG/NWIA/ATLAS/2010. *Space Application Centre, ISRO*, Ahmedabad, 2010.
24. Vass, K. K., Das, M. K., Srivastava, P. K. and Dey, S., Assessing the impact of climate change on inland fisheries in River Ganga and its plains in India. *Aquat. Ecosyst. Health Manage.*, 2009, **12**(2), 138–151.
25. Sundar, K. S. G. and Kittur, S., Can wetlands maintained for human use also help conserve biodiversity? Landscape-scale patterns of bird use of wetlands in an agricultural landscape in north India. *Biol. Conserv*., 2013, **168**, 49–56.
26. Bagchi, K., *The Ganges Delta*, University of Calcutta, Kolkata, 1944.
27. Rudra, K., Changing river courses in the western part of the Ganga–Brahmaputra delta. *Geomorphology*, 2014, **227**, 87–100.
28. Mukherjee, A., Fryar, A. E. and Howell, P. D., Regional hydrostratigraphy and groundwater flow modeling in the arsenic-affected areas of the western Bengal basin, West Bengal, India. *Hydrogeol. J.*, 2007, **15**(7), 1397–1418.
29. Jha, S., A note on whitenecked stokes. *Newsl. Birdwatchers*, 1998, **38**, 70–71.
30. Townshend, J. R. and Justice, C. O., Analysis of the dynamics of African vegetation using the normalized difference vegetation index. *Int. J. Remote Sensing*, 1986, **7**(11), 1435–1445.
31. McFeeters, S. K., The use of normalized difference water index (NDWI) in the delineation of open water features. *Int. J. Remote Sensing*, 1996, **17**(7), 1425–1432.
32. McGarigal, K., Cushman, S. A. and Neel, M. C., FRAGSTATS: spatial pattern analysis program for categorical maps. Computer software program developed at the University of Massachusetts, Amherst, 2002; http://www.umass.edu/landeco/research/fragstats/fragstats.html.
33. Jiang, H., Strittholt, J. R., Frost, P. A. and Slosser, N. C., The classification of late seral forests in the Pacific Northwest, USA using Landsat ETM+ imagery. *Remote Sensing Environ.*, 2004, **91**(3), 320–331.
34. Banerjee, M., A report on the impact of Farakka barrage on the human fabric. *South Asian Network on Dams, Rivers and People*, New Delhi, 1999.
35. Chapman, G. P., and Rudra, K., Water as foe, water as friend: lessons from Bengal's millennium flood. *J. South Asian Develop.*, 2007, **2**(1), 19–49.
36. Dunne, T. and Leopold, L. B., *Water in Environmental Planning*, Freeman, San Francisco, CA, 1978, p. 818.
37. Organisation for Economic Co-operation and Development (OECD), Guidelines for aid agencies for improved conservation and sustainable use of tropical and subtropical wetlands, Paris, 1996.
38. Biswas, B., Ghosh, D. C., Dasgupta, M. K., Trivedi, N., Timsina, J. and Dobermann, A., Integrated assessment of cropping systems in the Eastern Indo-Gangetic plain. *Field Crops Res.*, 2006, **99**(1), 35–47.
39. Harriss, J., What is happening in rural West Bengal? Agrarian Reform, growth and distribution. *Econ. Polit. Wkly.*, 1993, **28**, 1237–1247.
40. Mukherji, A., Shah, T. and Banerjee, P. S., Kick-starting a second green revolution in Bengal (India). *Econ. Polit. Wkly.*, 2012, **47**(18), 27–30.
41. Bardhan, P., Mookherjee, D. and Kumar, N., State-led or market-led green revolution? role of private irrigation investment vis-a-vis local government programs in West Bengal's farm productivity growth. *J. Develop. Econ.*, 2012, **99**(2), 222–235.
42. Bassi, N., Kumar, M. D., Sharma, A. and Pardha-Saradhi, P., Status of wetlands in India: a review of extent, ecosystem benefits, threats and management strategies. *J. Hydrol.: Regional Stud.*, 2014, **2**, 1–19.
43. Bardhan, P. and Mookherjee, D., Subsidized farm input programs and agricultural performance: a farm-level analysis of West Bengal's green revolution, 1982–1995. *Am. Econ. J.: Appl. Econ.*, 2011, **3**(4), 186–214.
44. ENVIS, Centre on Faunal Diversity; http://zsienvis.nic.in.

ACKNOWLEDGEMENT. The authors thank anonymous reviewers for their valuable and important suggestions for the improvement of this work.

Received 19 June 2016; revised accepted 26 December 2016

doi: 10.18520/cs/v112/i11/2263-2272