Groundwater recharge processes in an Asian mega-delta: hydrometric evidence from Bangladesh

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Table S1. Historical (1987-2015) extreme rainfall event statistics of nearby BWDB's rainfall observation stations.

Extreme Rainfall index	**Unit**	**Description of index**	**Bhuapur Rainfall station (Rajshahi)** [median]	**Savar Rainfall station (Dhaka)** [median]	**Bhuapur Site Field Test Period (2009-2010)**	**Savar Site Field Test Period (2009-2010)**
RX1day	mm	1-day maximum rainfall in a year	120	122	54	320
RX5day	mm	5-day maximum rainfall in a year	222	230	113	365
PRCPTOT	mm	Annual total rainfall	1771	1925	-	-
R99p	mm	Annual total rainfall when rainfall > 99^{th} percentile of 1987-2015 daily rainfall	221	263	-	-
R95p	mm	Annual total rainfall when rainfall > 95^{th} percentile of 1987-2015 daily rainfall	474	500	-	-
SDII	mm/day	Annual total rainfall divided by the number of wet days	17	17	-	-
R10mm	days	Total number of days in a year with rainfall > 10 mm	52	57	-	-
R20mm	days	Total number of days in a year with rainfall > 20 mm	30	32	-	-
CWD	days	Maximum number of consecutive wet days (rainfall > 0) in a year	11	12	-	-

Table S2. Dominant factors considered for the physical interpretation of cluster patterns.

Factors / Categories	Low	Moderate	High
Irrigation Abstraction (Q), mm (depth per unit area)	$Q \leq 150$	$350 > Q > 150$	$Q \geq 350$
Upper Silt-clay thickness (d), m	$d \leq 10$	$20 > d > 10$	$d \geq 20$
Land Classification by Flood Phase [a]	F3: 1.8 - 3m F4: > 3m	F2: 0.9 -1.8m	F0: < 0.3m F1: 0.3 - 0.9m

[a] Codes derive from Brammer (1988) classifying land in Bangladesh into five types of flood inundation depths: F0 (very high land having flood depth up to 0.3 m), F1 (high land having flood depth varying between 0.3 m and 0.9 m), F2 (medium land having flood depth varying between 0.9 m and 1.8 m), F3 (low land having flood depth varying between 1.2 m and 3.6 m) and F4 (very low land having flood depth more than > 3 m).

Table S3. A plausible physical interpretation of the cluster patterns with respect to the dominant factors mentioned in Table S2.

Cluster Category (Most common pattern)	Statistics of Agreement	Irrigational abstraction	Upper Silt-Clay thickness	Land types by Flood Phase	Generalised Comment
CL1 (Slight GWL declination with no change in seasonality)	15%	Low	Low	Mixed (F0/F1 dominates 50% of wells)	1.Low to moderate abstraction 2.Any thickness of silt-clay 3.Mixed land types
	12%	Low	Moderate	Mixed	
	10%	Low	High	Mixed	
	27%	Moderate	Low	Mixed (F0/F1 dominates 55% of wells)	
	18%	Moderate	Moderate	Mixed	
	15%	Moderate	High	Mixed	
CL 2 (Slight GWL declination with slight decrease in seasonality)	15%	Low	Moderate	Mixed (F0/F1 dominates 40% of wells)	1.Low to moderate abstraction 2.Any thickness of silt-clay 3.Mixed land types
	12%	Low	High	Mixed	
	22%	Moderate	Moderate	Mixed	
	32%	Moderate	Low	Mixed	
CL 3 (High GWL declination with diminishing seasonality)	25%	High	High	F0	1.Moderate to high abstraction 2.Moderate to high thickness of silt-clay 3.F0 type land
	9%	High	Moderate	F0	
	16%	Moderate	Moderate	F0	
	32%	Moderate	High	F0	
CL 4 (Moderate GWL declination with moderate decrease in seasonality)	12%	High	Low	F0 mixed with F1	1.Moderate abstraction 2.Any thickness of silt-clay 3.Mostly F0 mixed with F1 type land
	36%	Moderate	High	F0 mixed with F1	
	38%	Moderate	Low	F0 mixed with F1	
CL 5 (Slight GWL declination with increase in seasonality)	22%	High	Low	Mixed	1.Moderate to high abstraction 2.Low thickness of silt-clay 3.Mostly F2 or mixed type of land
	16%	Moderate	High	F2 mixed with F3/F4	
	60%	Moderate	Low	F2 Mixed with F1	

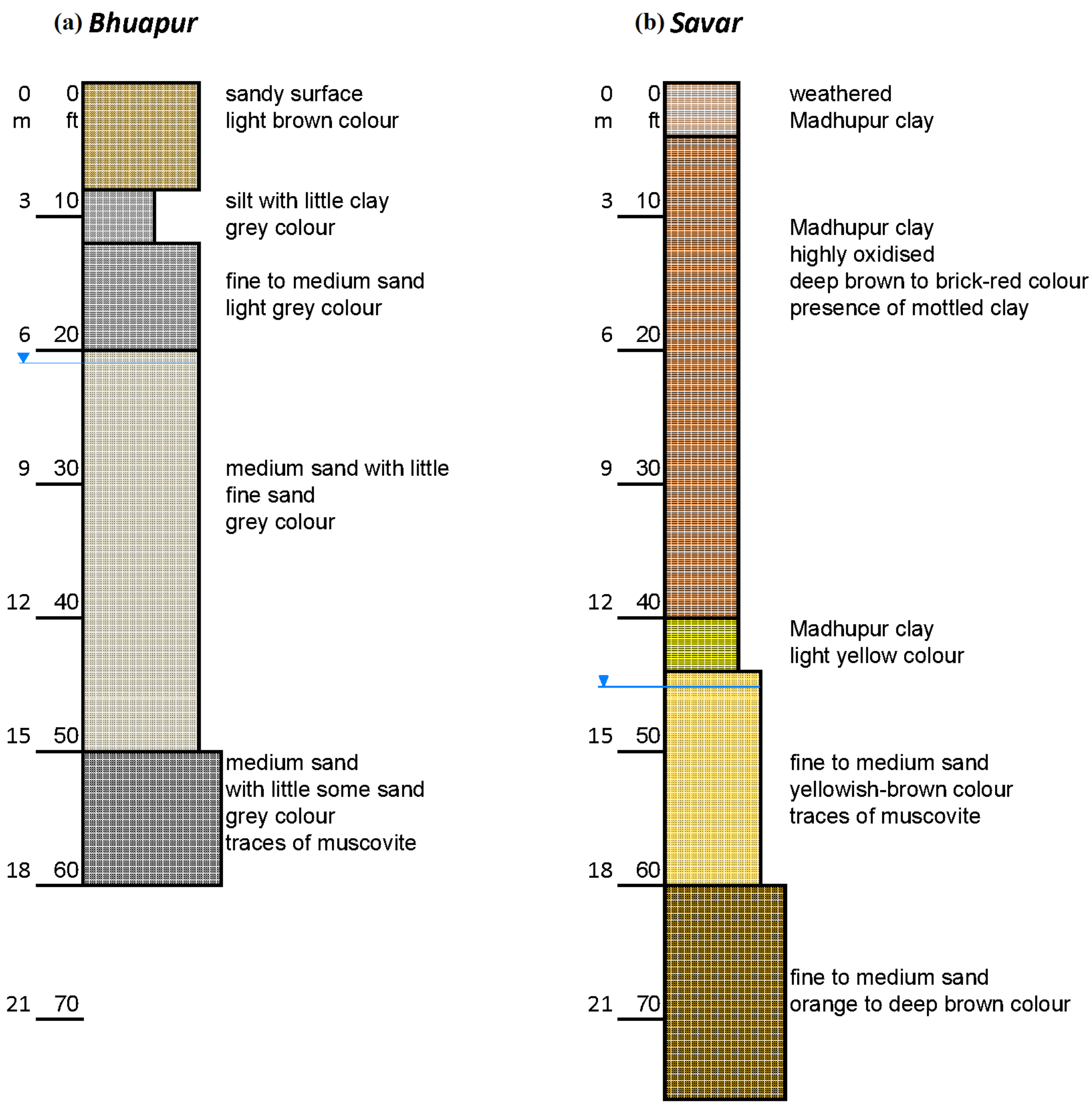

Fig. S1 (a) Detailed borehole lithological records at Bhuapur and (b) Savar sites as recorded from drilled core samples.

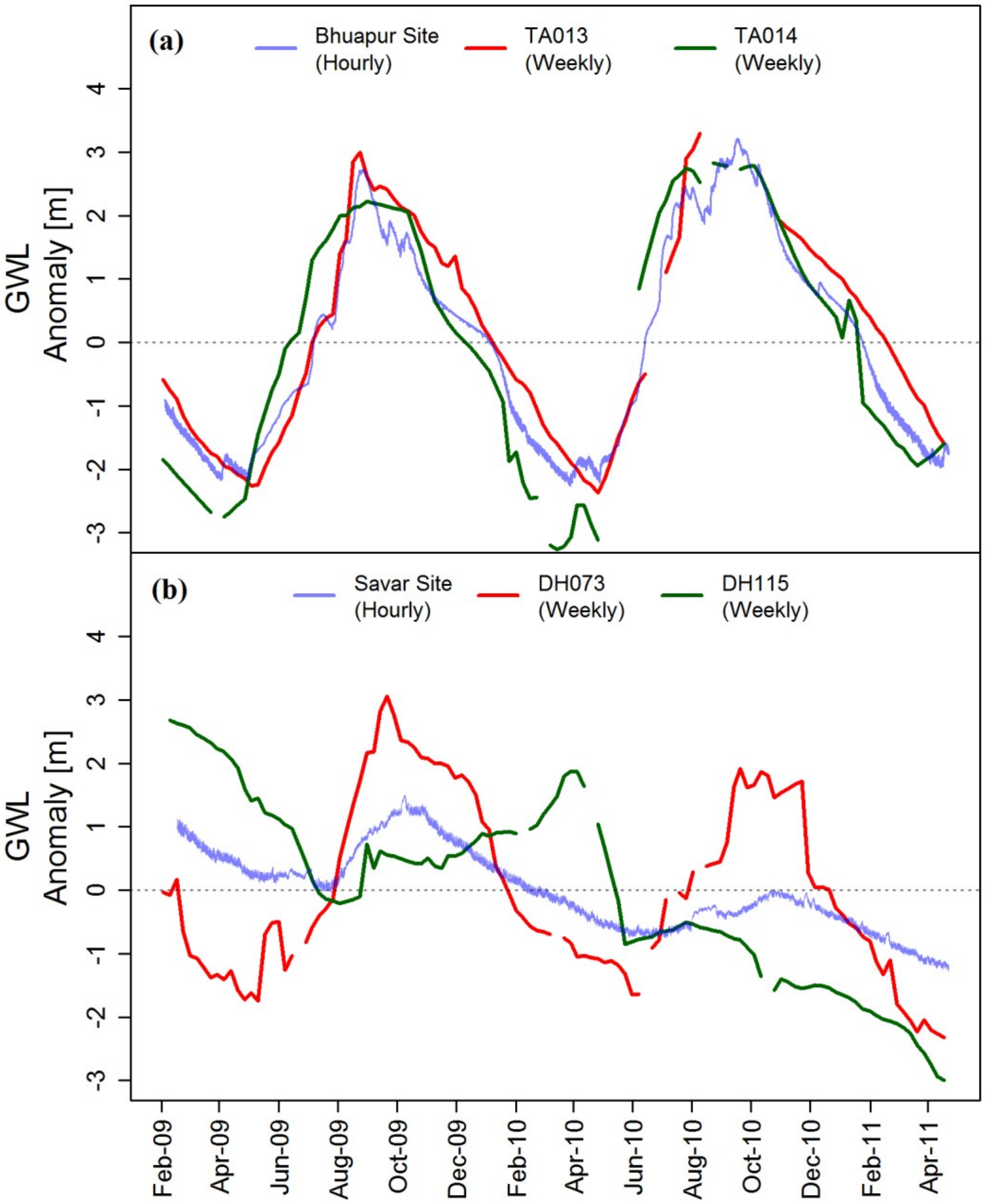

Fig. S2 (a) Hydrographs showing anomalies over 2 years (2009-2011) with respect to mean high-frequency (hourly) groundwater-level monitoring records and weekly groundwater-level records from the closest BWDB stations at Bhuapur and (b) Savar site, respectably.

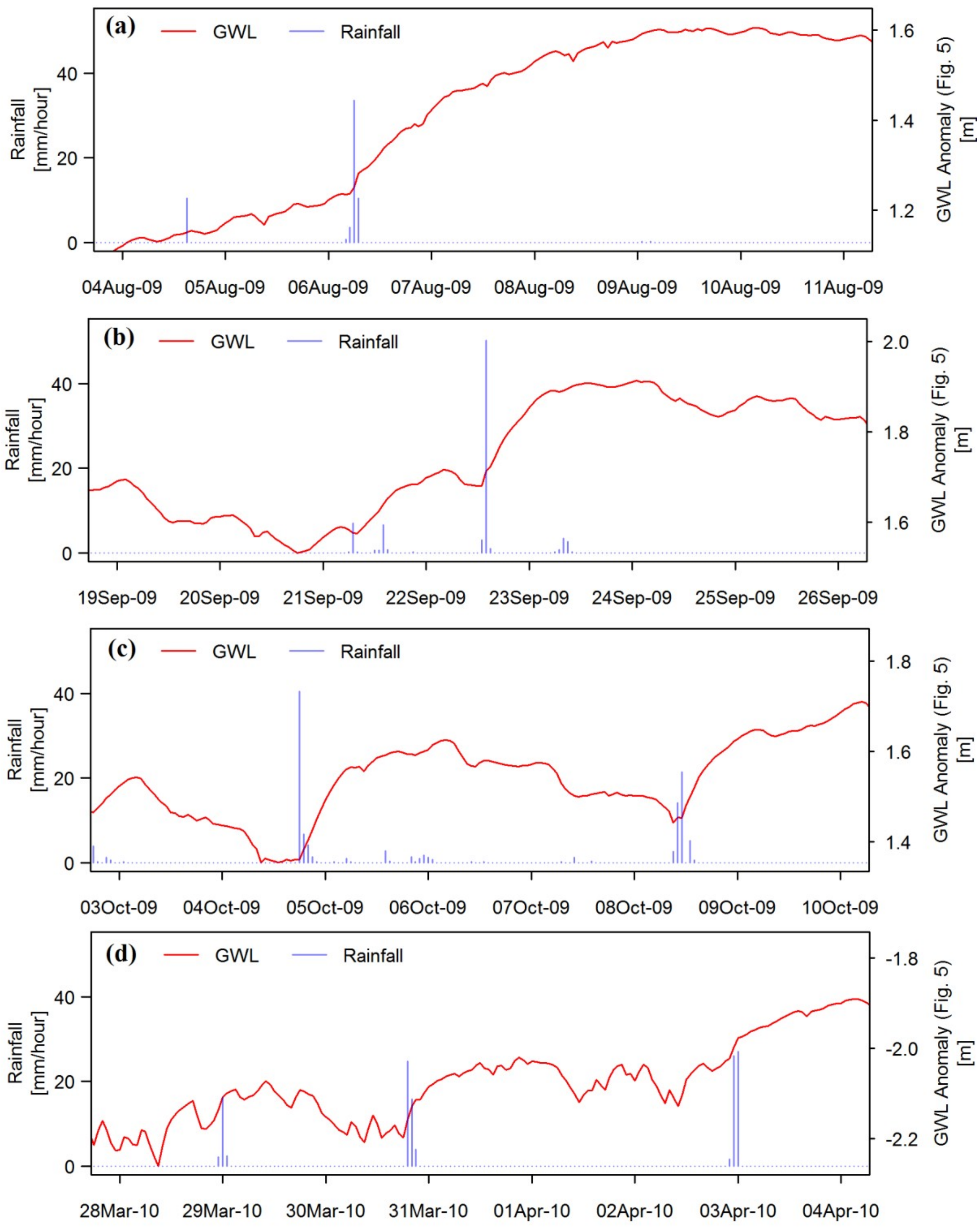

Fig. S3 Line plots show anomalies of groundwater levels and bar plots display corresponding recorded heavy rainfall events at Bhuapur: (a) 4 to 11 August 2009; (b) 19 to 26 September 2009; (c) 3 to 10 October 2009; and (d) 28 March to 4 April 2010.

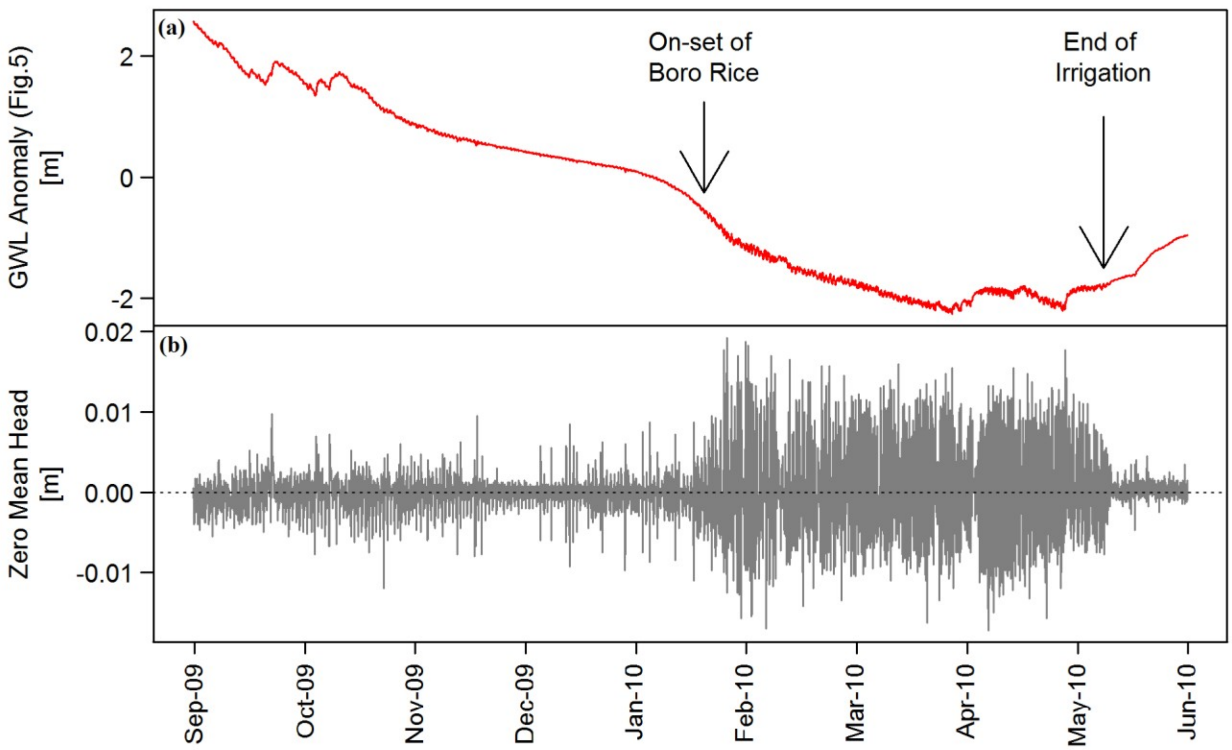

Fig. S4 (a) Hydrograph showing a recession period highlighted in Fig. 5 (d) at Bhuapur site: hourly, corrected groundwater levels for barometric pressure, and (b) hourly fluctuations in groundwater levels, calculated by subtracting a 1-hr moving average from the observed groundwater levels shown in panel (a).

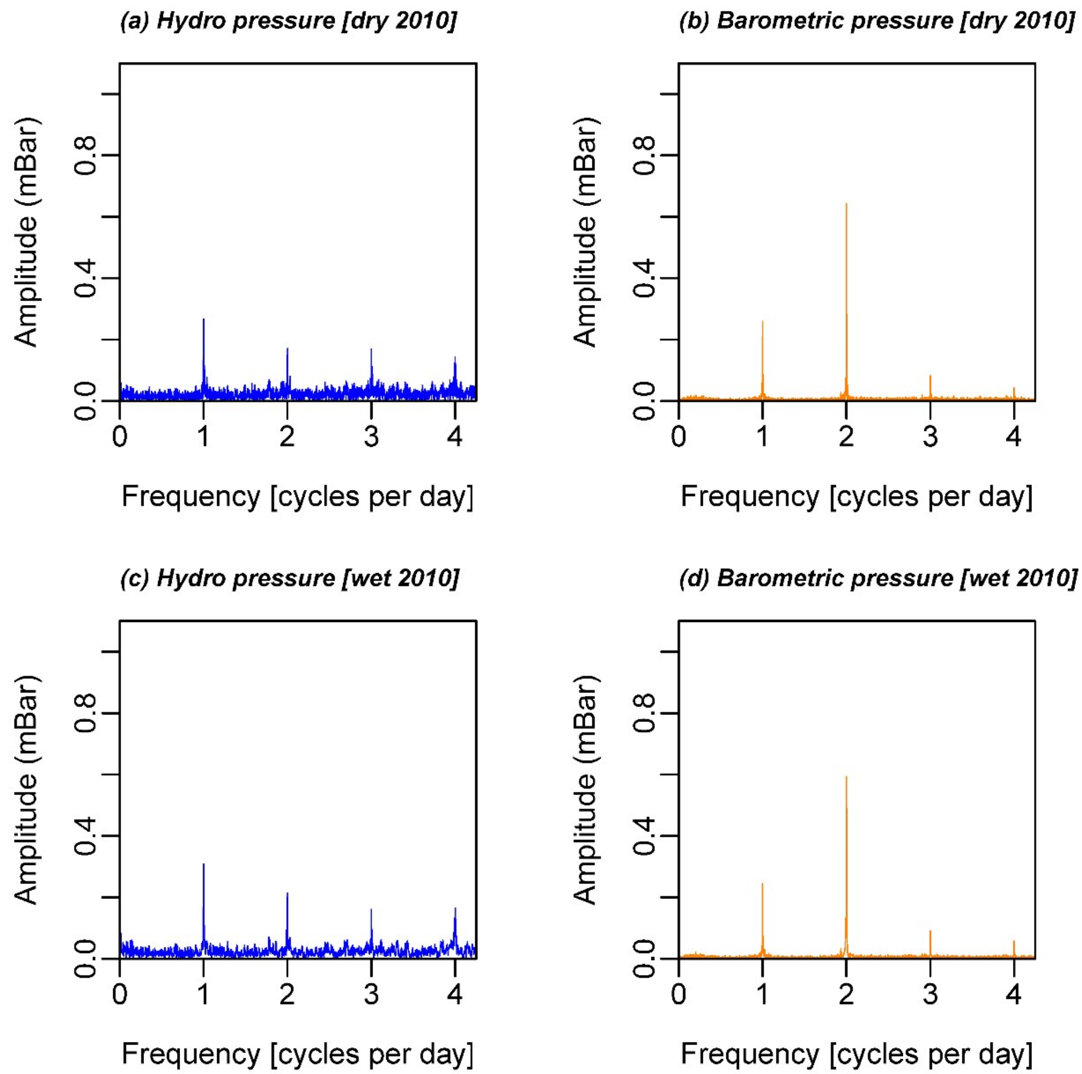

Fig. S5 Dominant modes or frequencies and their corresponding amplitudes in the observed hydrostatic (blue) and atmospheric or barometric (orange) pressure at Bhuapur site during (a and b) dry and (c and d) wet seasons revealed by an analysis of the Fast Fourier transform (FFT) algorithm in R programming language.

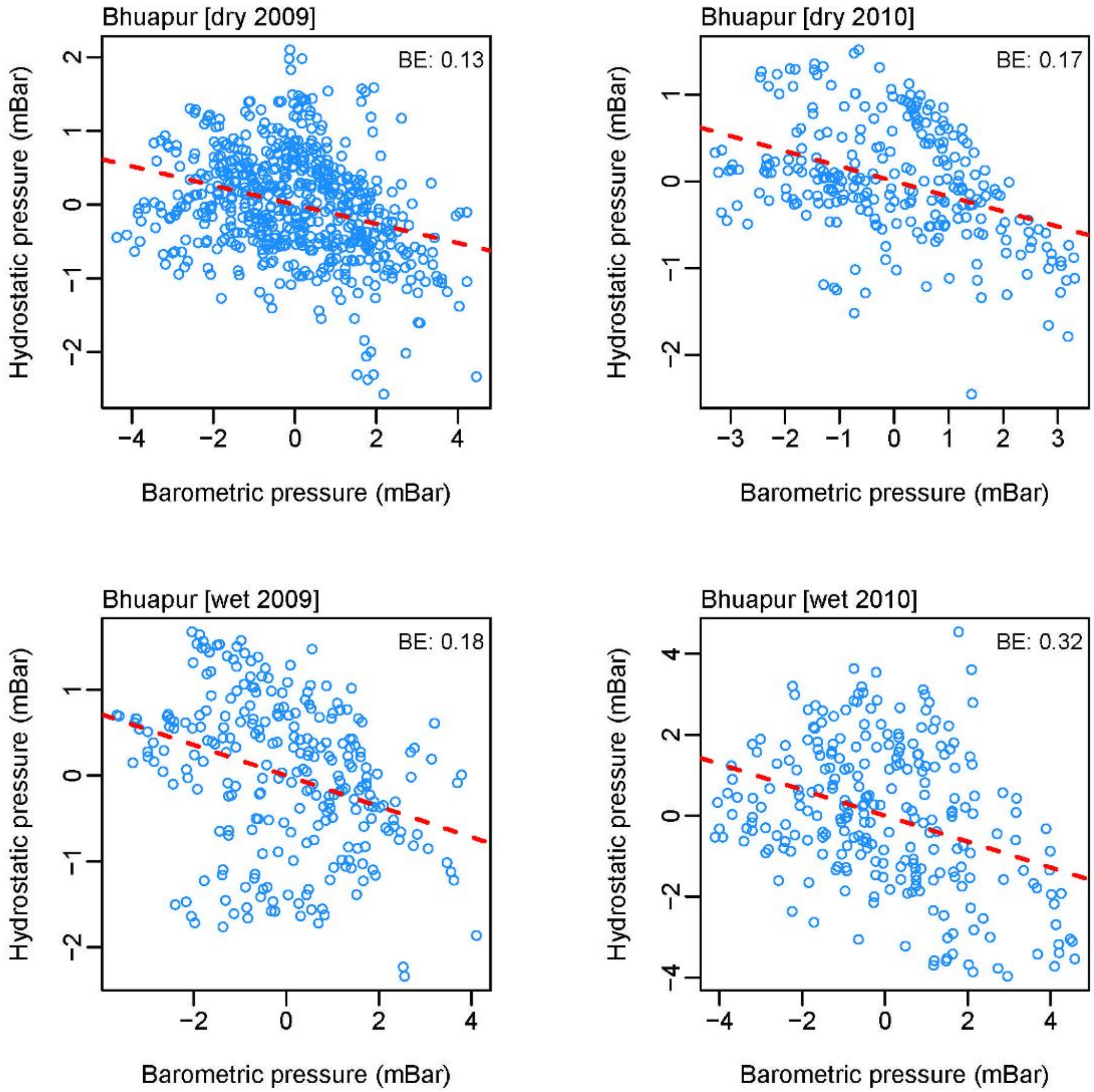

Fig. S6. Barometric efficiency (BE) determined from weak but statistically significant ($p < 0.001$) the inverse relationship between barometric pressure and groundwater pressure and the values of the linear regression slope at Bhuapur site during 2009 wet and dry season (left panel) and 2010 (right panel); computed values (13% to 32%) are similar to the BE (36%) computed from the ratio of the S2 signal in groundwater levels and barometric pressure (Fig. S5) following the method of Acworth et al. (2015).

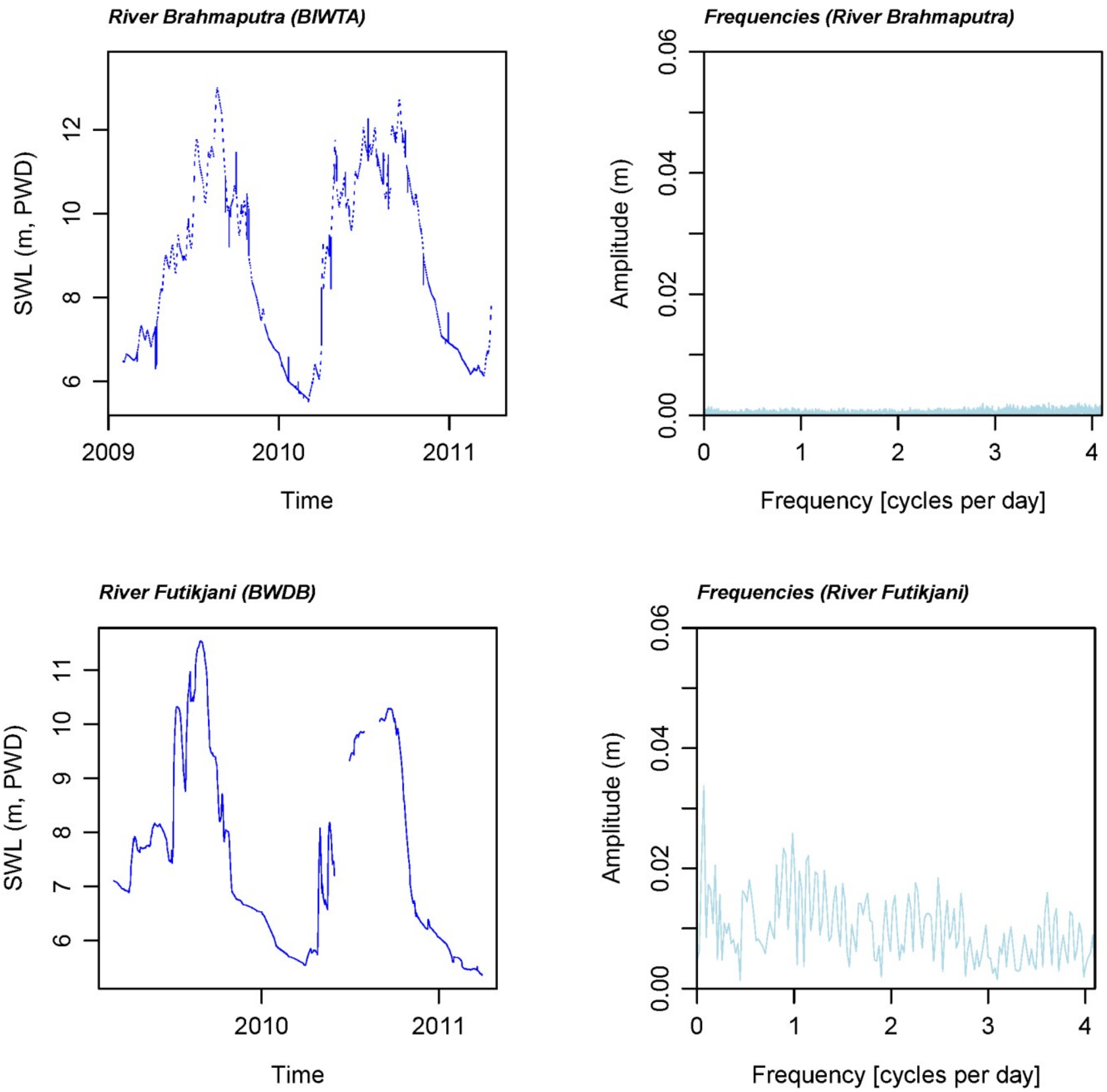

Fig. S7. Dominant modes or frequencies and their corresponding amplitudes in the surface water-level time-series records at Bhuapur site (top: hourly records from River Brahmaputra; bottom: daily records from River Futikjani) have been revealed by an analysis of the Fast Fourier transform (FFT) algorithm in R programming language.

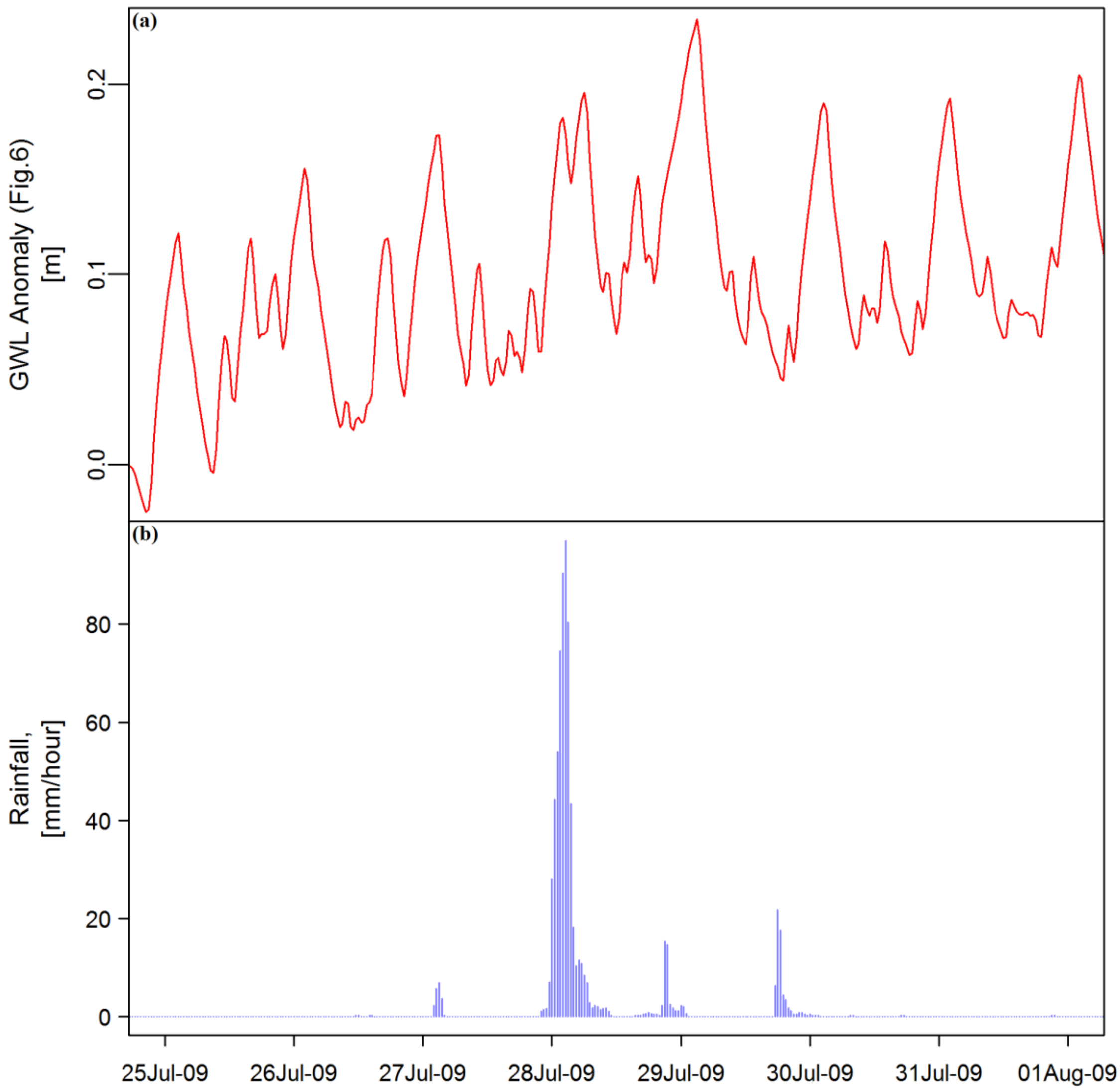

Fig. S8. High-frequency groundwater-level anomalies (a) and rainfall including an extreme rainfall event (320 mm on 28 July 2009) as shown in Fig. 6 (e) at Savar site.

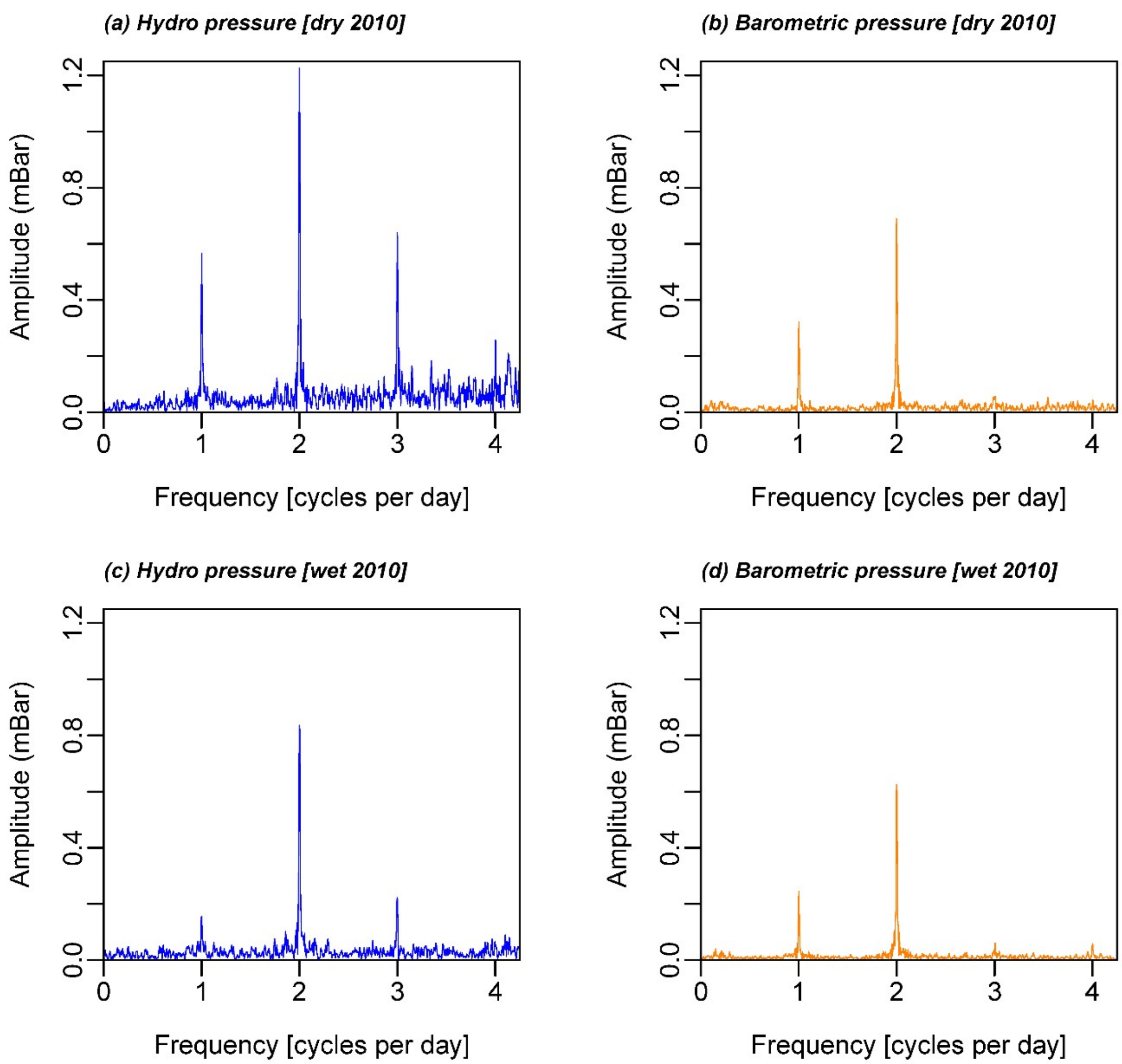

Fig. S9. Dominant modes or frequencies and their corresponding amplitudes in the observed hydrostatic (blue) and barometric (orange) pressure at Savar site during (a and b) dry and (c and d) wet seasons revealed by an analysis of the Fast Fourier transform (FFT) algorithm in R programming language.

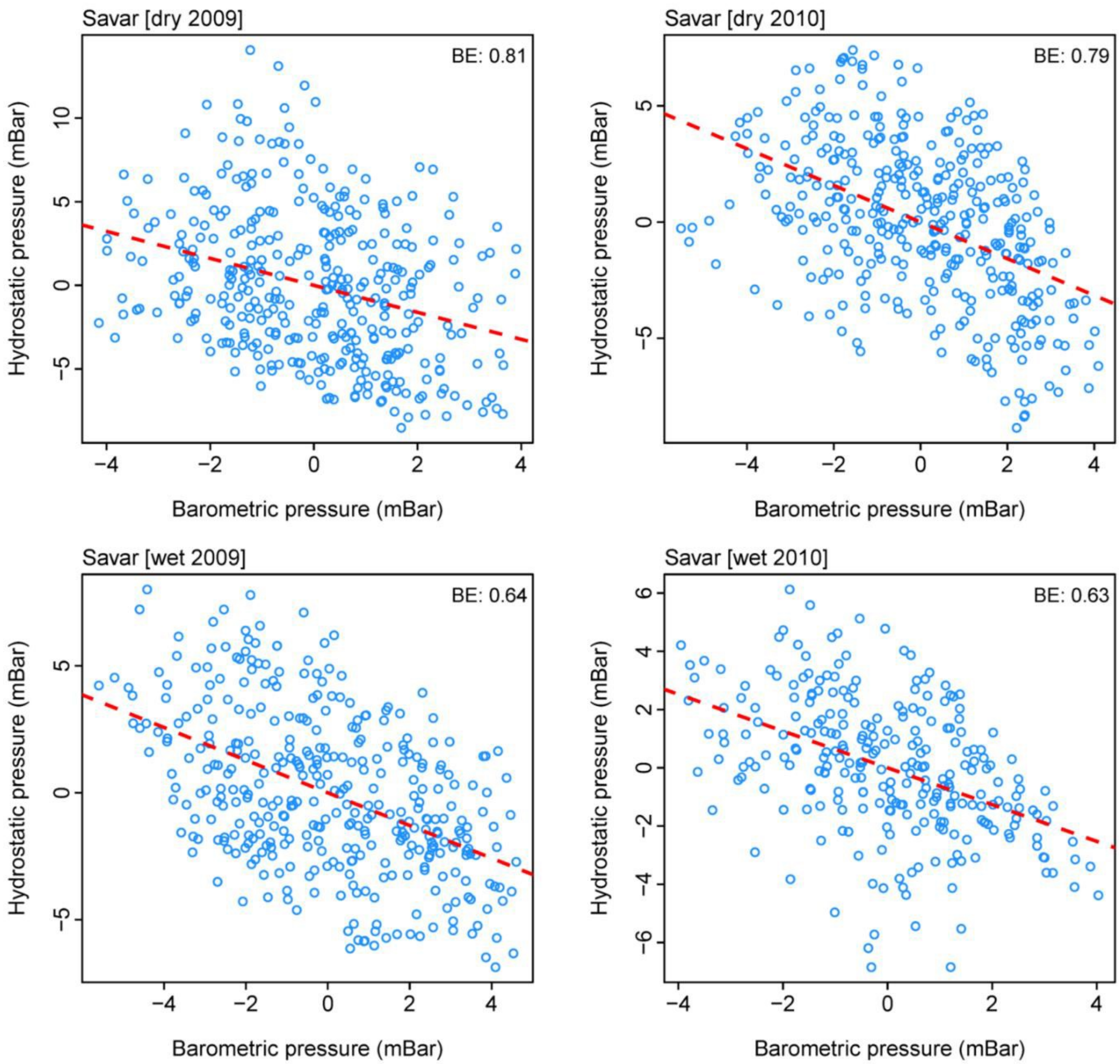

Fig. S10. Barometric efficiency (BE) determined from weak but statistically significant ($p < 0.001$) the inverse relationship between barometric pressure and groundwater pressure and the values of the linear regression slope at Savar site during 2009 wet and dry season (left panel) and 2010 (right panel); computed values (63% to 81%), substantially greater than the BE at Bhuapur, are consistent with the value of >100%, likely influenced by diurnal pumping, that is computed from the ratio of the S2 signal in groundwater levels and barometric pressure (Fig. S9) following the method of Acworth et al. (2015) .

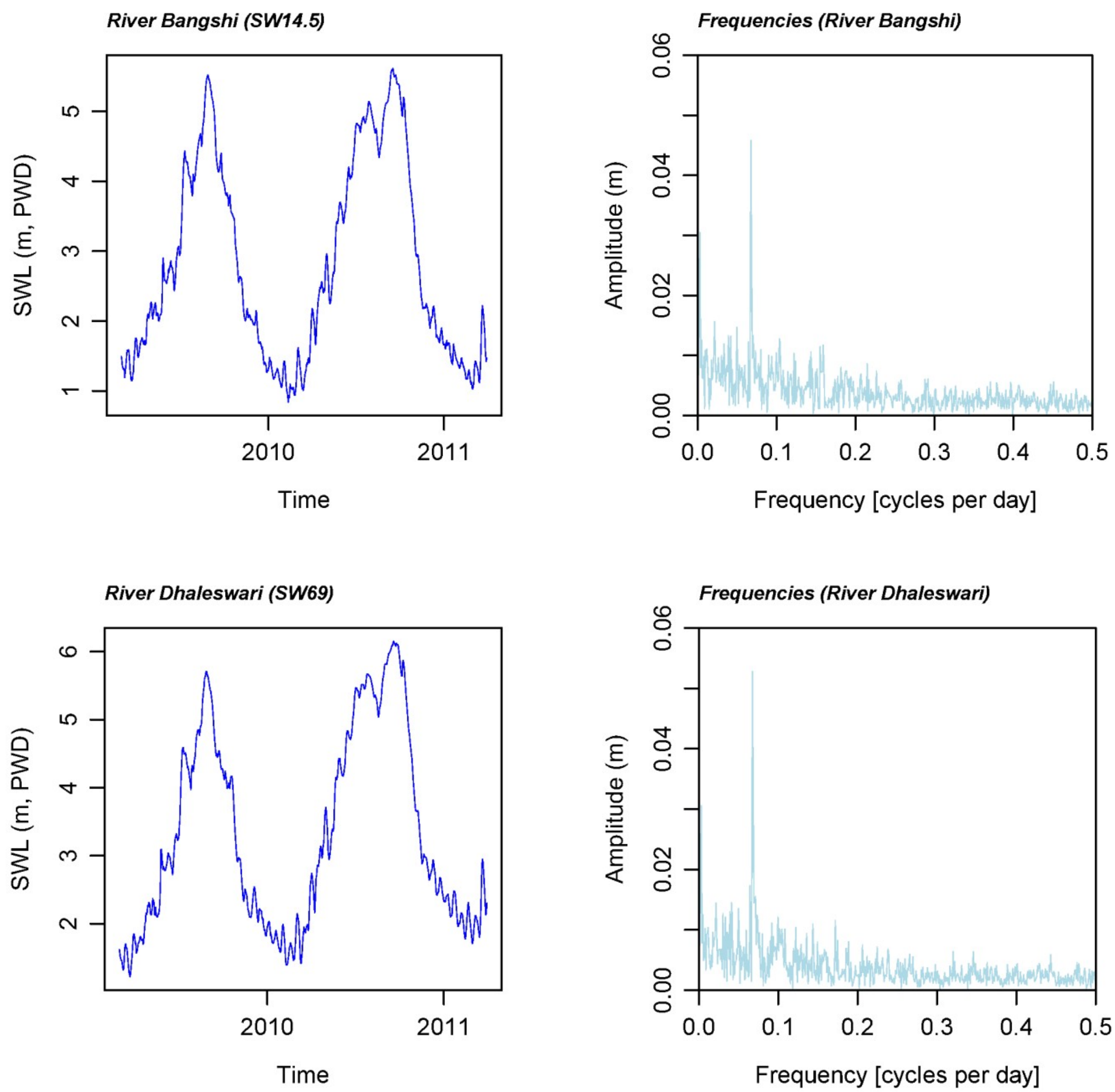

Fig. S11. Dominant modes or frequencies and their corresponding amplitudes in the surface water-level time-series records in Savar site (top: daily records from River Bangshi; bottom: daily records from River Dhaleswari) have been revealed by an analysis of the Fast Fourier transform (FFT) algorithm in R programming language.

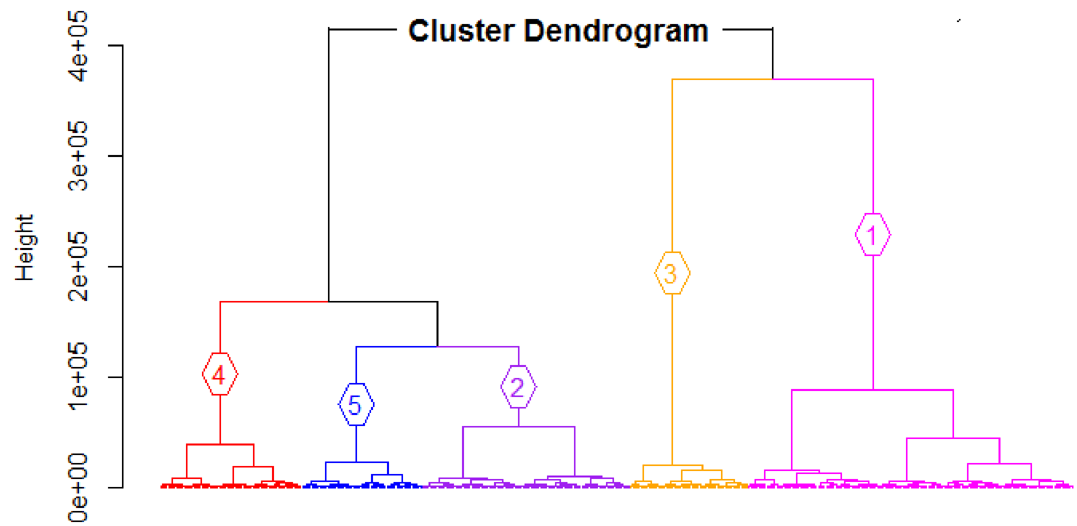

Figure S12. Cluster dendrogram formed by the hierarchical method (i.e., Canberra dissimilarity measure for Ward.D2 Linkage cut at cluster numbers *k*=5) of groundwater time series for the period 1994-2013; the height of each U-shaped lines on the vertical axis, represents the distance between the data points being connected so that the higher the height of the branch (i.e., U shaped lines), the less similar the observations are. Note that, the proximity of two observations along the horizontal axis cannot be taken as similarity criteria.

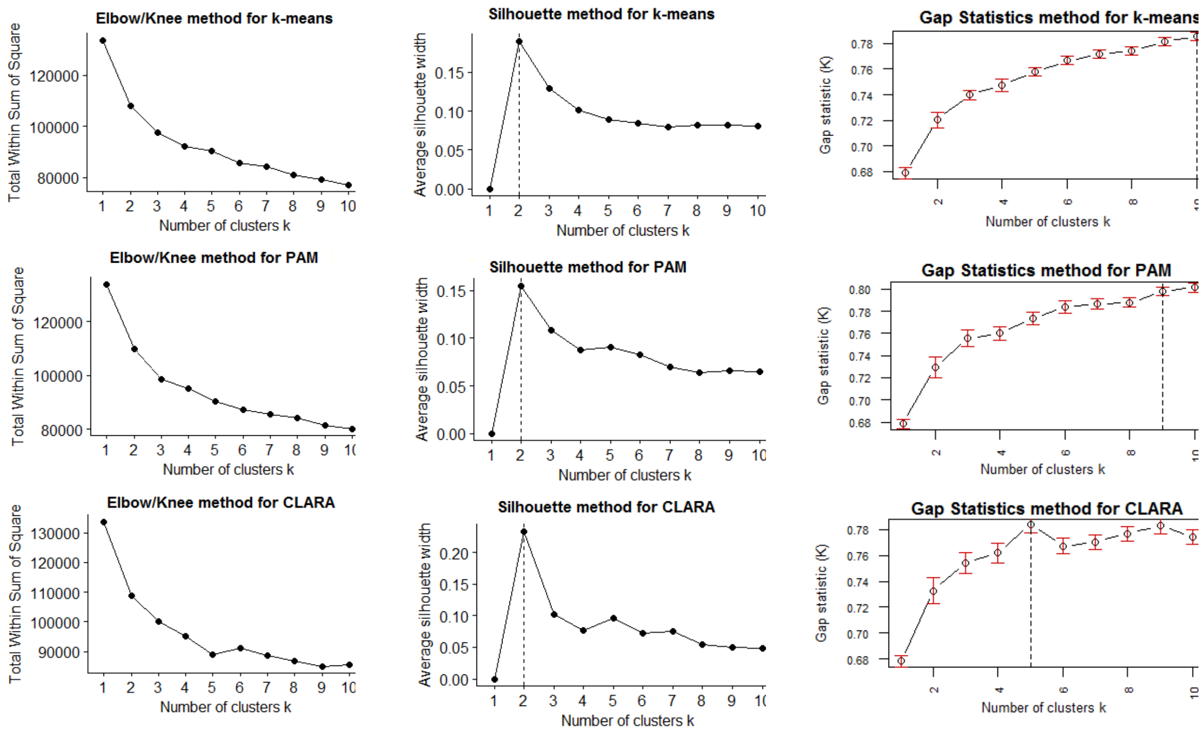

Fig. S13: Graphs suggesting optimal number of clusters (*k*) estimated by non-hierarchical partitioning functions namely k-means, PAM and CLARA; indicators for the optimal number of clusters (*k*) are the total within sum of squares in the 'Elbow/Knee' method, the average silhouette width in the 'Silhouette' method, and gap statistics (K) in the 'Gap-stat' method. The graphs for the Elbow method (left panel) in all partitioning functions do not show any clear indication of sharp turning; the Silhouette method (middle panel) consistently suggests two as the optimal number of clusters; and the Gap statistics method (right panel) proposes different cluster numbers (*k*) ranging between 5 to 10 for different partitioning functions.

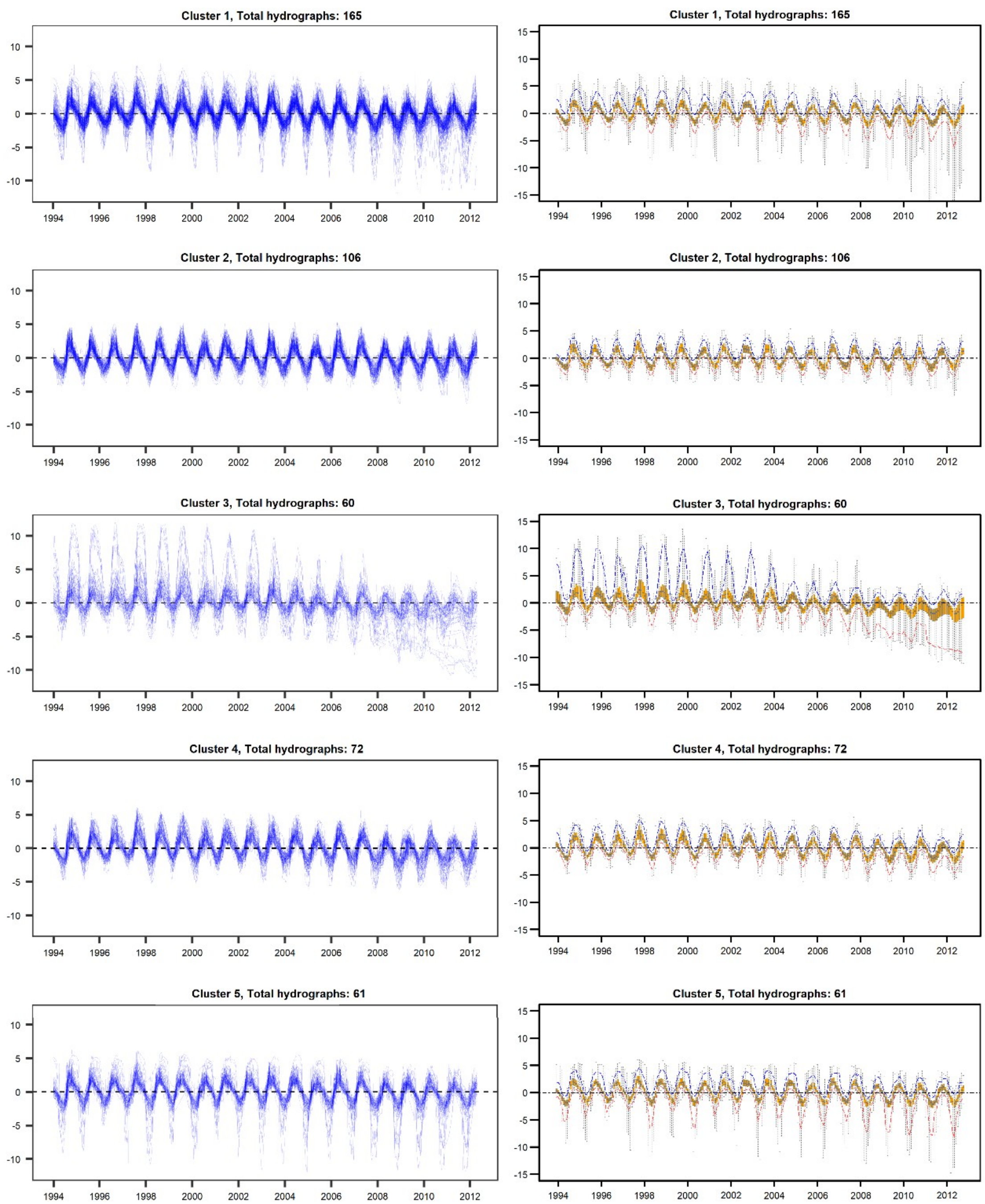

Fig. S14 Time series of all groundwater hydrographs against the long-term (1994-2013) mean for each of the five hierarchical clusters using Ward.D2 Linkage with pre-defined Canberra function (left panel); Boxplots showing median (grey), 5th percentile (red) and 95th percentile (blue) of groundwater level time series of each of the said clusters (right panel).

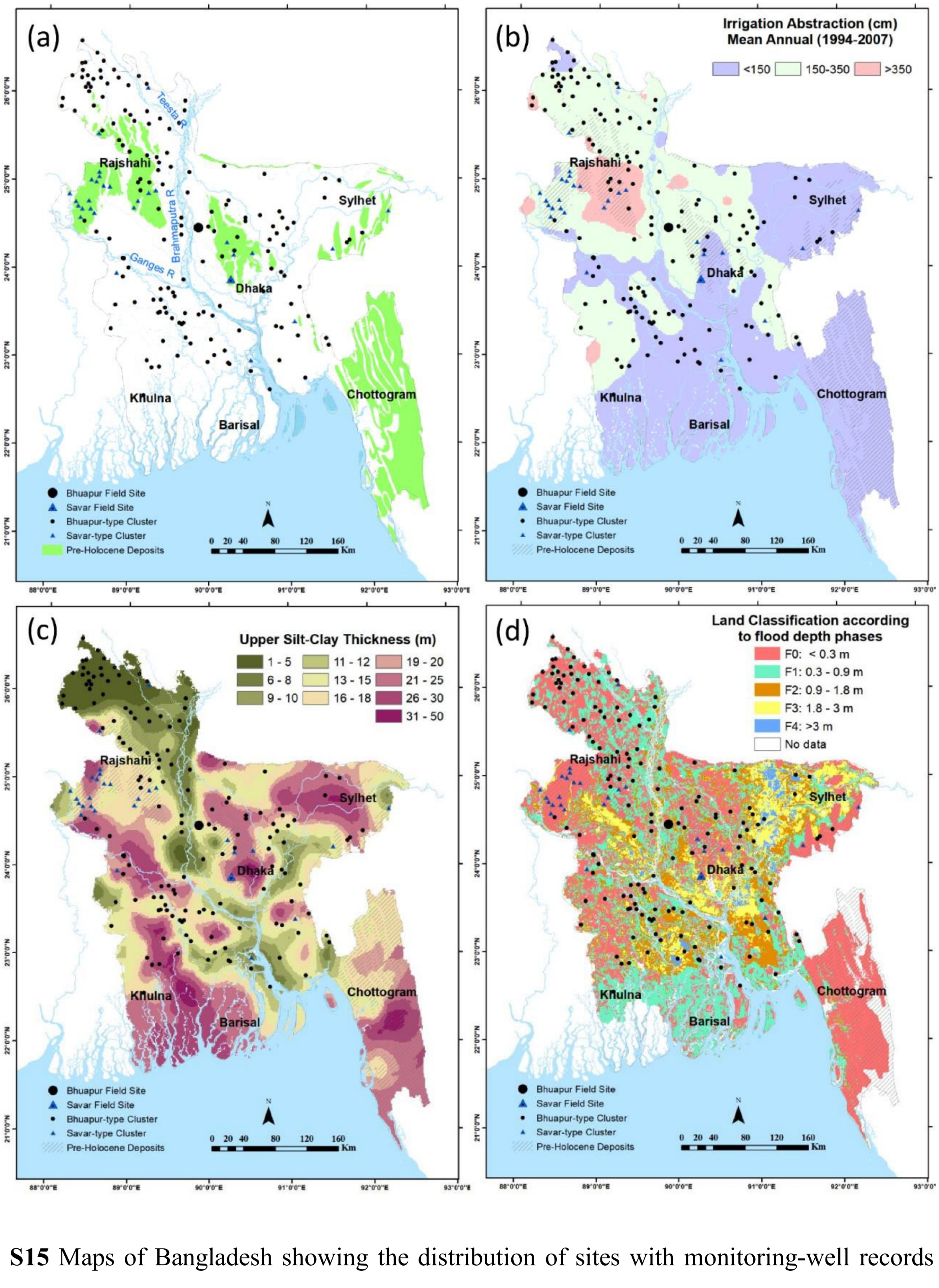

Fig. S15 Maps of Bangladesh showing the distribution of sites with monitoring-well records showing Bhuapur-type (CL1) and Savar-type (CL3) statistical clusters overlaid on (a) surface geology, (b) irrigation abstraction, (c) upper silt-clay thickness, and (d) annual flood depth phases (see caption for Table S2 for definition of these).

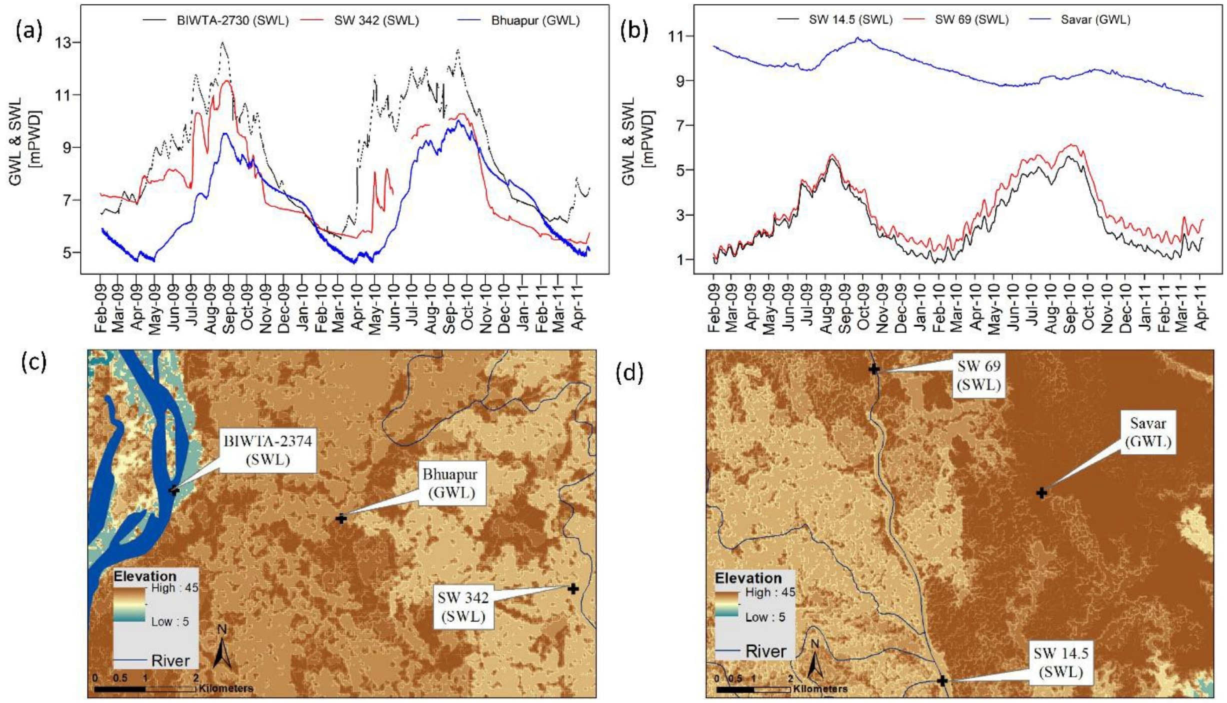

Fig. S16 Time-series plots of recorded hydraulic heads over a period of 2009 to 2011: (a) groundwater levels at Bhuapur and surface water heads of River Brahmaputra (station number BIWTA-2374) and River Futikjani (station number SW 342), (b) groundwater levels at Savar and surface water levels of River Bangshi (station number SW 69) and River Dhaleswari (station number SW 14.5). Maps show the locations of monitoring gauges at (c) Bhuapur and (d) Savar. Note that both elevations for high-resolution monitoring sites were recorded using a hand-held GPS and cross-checked with the SRTM elevation model data; these present considerably greater uncertainty in absolute elevation than the Public Works Datum (PWD) established by the Bangladesh Water Development Board. Savar is located on an elevated plateau thus showing elevated heads compared to the surface water monitoring sites that are in lowlands.