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Hydrological Load and a Review of Hydro-Mechanical Behaviour of the Bengal Aquifer System

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ABSTRACT: In traditional hydrogeologic interpretation, the contribution of loading impacts and the associated hydro-mechanical aquifer behaviour are usually ignored. In certain circumstances however, they may have significant implications for water budget studies, groundwater monitoring and therefore resource assessment. Hydrological loading influences on groundwater in the Bengal Aquifer System (BAS) have recently been recognized at individual sites in Bangladesh. This review accumulates evidences to extend knowledge of BAS hydro-mechanical behaviour, to establish the significance of these coupled processes which under-pin groundwater variations in this environment. From the review, it may be realized that aquifer hydro-mechanical behaviour needs to be more fully considered in the BAS to interpret groundwater level data and groundwater storage changes. Therefore, further investigation of the scale and implications of hydro-mechanical coupling in specific hydrogeological settings and in the context of specific loading sources are needed, so that the effects may be properly recognized.

Keywords: Bengal Aquifer System; Hydro-Mechanical Behaviour; Hydrological Loading

INTRODUCTION

Within the Indo Gangetic Basin (IGB) region, the highly productive, fluvio-deltaic, Bengal Aquifer System (BAS) is the largest aquifer in south Asia, underlying almost the whole of Bangladesh and is of enormous strategic importance in providing the water requirements for more than 160 million people (UN-DESA 2017). Bangladesh is nearly 100% groundwater dependent as a country, for drinking and domestic use (Ahmed et al., 2004; Jakariya et al., 2007), and ~75% dependent for irrigation and food security (Scott and Sharma 2009) and also for major industrial use (Arup 2016), which made the country obtain sixth position among top groundwater user countries (Ahmed, 2021). But this precious resource is subject to multiple threats; arsenic commonly exceeds safe levels in shallow groundwater (BGS and DPHE, 2001); salinity occurs variously in shallow and deep groundwater in the coastal region (Sultana et al., 2015; Ayers et al., 2016) and the ever-rising abstraction is reflected in declining groundwater levels in Dhaka city (Islam et al., 2021), in the Barind area and in the major industrial belts, threatening security of access.

Therefore, a robust regime for groundwater monitoring is of vital importance in the BAS, for which the Bangladesh Water Development Board (BWDB) manages a national network of more than 1035 monitoring boreholes placed at depths from <5 to 77 m (Shamsudduha et al., 2011), which has been extended by 111 additional monitoring sites at up to 300 m depth (BWDB, 2013). The approach to groundwater resource monitoring and assessment throughout the Bengal Basin relies on the traditional assumption that groundwater-level fluctuations are due entirely to recharge during the monsoon period and due to drainage during the dry season, locally superimposed by the effects of pumping. Recharge estimation (Shamsudduha et al., 2011), and assessments of change in storage (Shamsudduha et al., 2012) have all previously been based on hydraulic analyses of groundwater hydrographs and the assumption of de-coupled behavior. All groundwater flow modeling applied to the BAS, either for groundwater resource estimation (Michael and Voss, 2009b) or

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for solute transport models supporting vulnerability assessments (Michael and Khan, 2016; Hoque and Burgess, 2020) have also relied on the de-coupling assumption. However, the basis for these existing de-coupled interpretations may be flawed as it ignores the mechanical response of the aquifer to changes in surface hydrological load (e.g. from individual rainfall and flood events during the monsoon, and by drainage and drying of the land surface during the dry season) (Bardsley and Campbell, 1995; Van der Kamp, 2017).

A unique and classic example of the effect of surface loading on groundwater has been given by Jacob (1939) who showed an instantaneous rise of water level in a confined aquifer in response to the load exerted by a passing railroad train, as documented in text books (Freeze and Cherry 1979; Domenico and Schwartz 1998) (Fig. 1a). A similar example is given in a study in southern Saskatchewan, Canada (Van der Kamp and Schmidt, 1997) where the response in a piezometer installed in a thick aquitard is due to the placing of a 39-ton vehicle in the 'sensing area' of the piezometer (Fig. 1b).

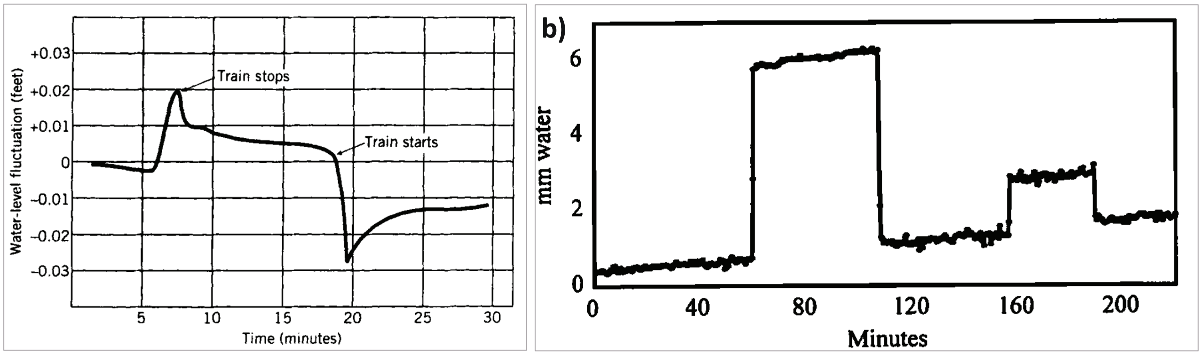


Figure 1: a) Water-level Fluctuations in an Observation Well Near a Railroad Station, after Freeze and Cherry (1979); b) Response of Piezometer to Loading by a 39-ton Vehicle Located at Distances of 21 m and 39 m, after Van der Kamp and Schmidt (1997)

"Surface hydrological loading" has been considered a "neglected factor" (Bardsley and Campbell, 1995) and even as "hidden information" (Van der Kamp, 2017) in time series analysis of groundwater pressure. Ground deformation driven by hydrological load has been recorded in the vertical component of GPS time series in many locations worldwide, including California (Argus et al., 2014), Italy (Vitagliano et al., 2017), Australia (Han, 2017), Himalaya (Larochelle et al., 2018) which has now become an promising area of research. Hydro-mechanical responses of the aquifer have been identified in a variety of hydrological and hydrogeological settings globally. A 300 m deep well in Kansas, USA, captures loading effect of an 86 mm rainfall event (Sophocleous et al., 2006) and in coastal aquifers, identical groundwater oscillations analogous to semidiurnal ocean tides have been interpreted as the outcome of tidal loading influences (Merritt, 2004). These studies are few in number nevertheless in 2000 (Bardsley and Campbell, 2000) predicted that hydro-mechanical coupling may be significant across the alluvial plains of the Bengal Basin. The mechanical response has recently been recognized for the BAS in preliminary investigations at individual sites in Bangladesh (Burgess et al., 2017) and this review gathers evidences of hydro-mechanical behaviour of BAS. The broader scientific question in this review is "Is groundwater perturbation by mechanical loading due to land surface flooding a widespread phenomenon?" If so, how it is impacting the current interpretation of groundwater level hydrographs and what are the significance of it in terms of groundwater level monitoring.

THEORETICAL CONCEPTS

Sediments may experience loading from a variety of natural sources (e.g. atmospheric pressure, rainfall, surface flooding, ice sheets, ocean tides, and Earth tides) as well as from anthropogenic sources (e.g. surface water reservoirs). In response to changes in loading, a coupling of the hydraulic and mechanical conditions in subsurface porous materials causes the groundwater pressure head to change and the aquifer materials to deform as the changes in applied stress are distributed between the fluid and the solid components of the aquifer (Rojstaczer and Agnew, 1989; Merritt, 2004). Coupling between changes in stress and fluid pressure in geological materials is the basis of poro-elasticity (Wang, 2000) and this fundamental concept of poro-elasticity for elastic porous media have been established by (Biot, 1955).

It is useful to start with the propagation of hydraulic impulse in a porous medium. The pure 1-D hydraulic propagation of a sinusoidal hydraulic signal in a confined homogeneous aquifer proceeds as follows (Todd, 2008)

$$a = a_0\, exp(-x\sqrt{\frac{\pi S}{t_0 T}})\; sin(\frac{2\pi t}{t_0} - x\sqrt{\frac{\pi S}{t_0 T}}) \quad \ldots\ldots\ldots\ldots\ldots \quad \ldots Eq.1$$

where a is the amplitude of hydraulic signal at distance x and time t, a_0 is the amplitude of the hydraulic signal of the source, x is the distance from the source, t_0 is the period of hydraulic signal, S is aquifer storativity (dimensionless) and T is aquifer transmissivity. (Note that S/T could be replaced by S_s/K, which is 1/D, where $D(=\frac{K}{S_s})$ is the aquifer hydraulic diffusivity), K is the hydraulic conductivity and S_s is the specific storage.

Pure downward propagation of a surface hydraulic signal, would exhibit exponential attenuation in amplitude and a time delay (lag) with depth as follows:

$$\mathbf{t_L = x\sqrt{\frac{t_0 S}{4\pi T}}} \quad \ldots\ldots\ldots\ldots \quad \ldots \mathbf{Eq.\ 2}$$

$$\mathbf{a_x = a_0\, exp(-x\sqrt{\frac{\pi S}{t_0 T}})} \quad \ldots\ldots\ \ldots\ldots \ldots \mathbf{Eq.\ 3}$$

where $\mathbf{t_L}$ is the time lag relative to the signal at the source, a_x is the amplitude of the diffusive hydraulic response observed at the depth x. If a_z is the amplitude of the hydraulic signal at depth Z. C is the 'propagation depth', then the expression becomes

$$\mathbf{a_Z = a_0\, exp\left[-\frac{Z\pi}{C}\right]} \quad \ldots\ldots\ldots\ldots\ldots \mathbf{Eq.\ 4}$$

If C is related to t_0, the period of the hydraulic signal, and expressed as the equation:

$$\mathbf{C = (\pi t_0 D)^{\frac{1}{2}}} \quad \ldots\ldots\ldots\ldots\ldots \mathbf{Eq.\ 5}$$

The propagation depth, C, is taken as the depth where the amplitude of the response is 4% of the amplitude of the source signal (Van der Kamp and Maathuis 1991). Because C is proportional to it is unlikely for deep aquifers to be affected hydraulically by diurnal, or even lunar signals propagating through heterogeneous sediments with low hydraulic diffusivity, as the higher the signal frequency, the smaller is the propagation depth. Therefore, where a groundwater pressure response is seen to be insufficiently lagged or has an amplitude which is not sufficiently decayed relative to the hydraulic signal of the source, then mechanical loading should be considered as an explanation of the observation.

Hydro-mechanical behaviour can be introduced simply in terms of the principle of effective stress which is defined as the part of the total stress that is borne by the granular skeleton of the aquifer material and is not borne by fluid. The total stress $\boldsymbol{\sigma_T}$ can be decomposed into the sum of the effective stress $\boldsymbol{\sigma_e}$ and the porewater pressure $\mathbf{P}$ and can be written as Eq. 6.

$$\mathbf{\sigma_T\ = \sigma_e + P} \quad \ldots\ldots\ldots\ldots\ldots \mathbf{Eq.\ 6}$$

If the total stress, which is the combined weight of overlying rock and water, does not change with time ($\partial\sigma_T = 0$) and the equation can be written as:

$$\mathbf{\partial\sigma_e = -\partial P} \quad \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{Eq.\ 7}$$

Therefore, an increase of pore fluid pressure decreases the effective stress by an equal amount and the skeleton of the aquifer expands in consequence; conversely, vice versa happens.

This inter-dependence is further expressed through the fact that deformation in response to pore pressure change, is determined by compressibility of the sediment (α) (a mechanical property), which also governs aquifer storativity and through this affects the hydraulic behaviour of sediments (Freeze and Cherry 1979). α is defined as the ratio of change in strain $\partial\epsilon$ to the change in effective stress $\partial\sigma_e$ which is simply inverse to the modulus of elasticity or Young's Modulus ($\mathbf{E}$) (in one dimension) (Freeze and Cherry 1979), and can be written by the following expression:

$$\mathbf{\alpha = \frac{\partial\epsilon}{\partial\sigma_e} = \frac{1}{E}} \quad \ldots\ldots\ldots\ldots\ldots \mathbf{Eq.\ 8}$$

Under confined conditions, the concept of Specific storage (S_S) reflects the aquifer hydro-mechanical behaviour (Green and Wang 1990), as water is expelled due to volume changes brought about as a consequence of stress reorganisation in response to head changes, as described in the following expression:

$$\mathbf{S_s = \rho g(\alpha{+}n\beta)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{Eq.\ 9}$$

Here, β is water compressibility, ρ is density of water, and n is the porosity.

Considering only vertical groundwater flow in sediments of infinite extent under a vertical load, the change in groundwater pressure with time would be the product of both flow-induced pressure changes and mechanical load-induced pressure changes and can be presented by the expression below (Rojstaczer and Agnew 1989; Van der Kamp and Schmidt 1997):

$$\mathbf{\frac{\partial p}{\partial t} = D\frac{\partial^2 p}{\partial z^2} + LE\frac{\partial \sigma}{\partial t}} \qquad \ldots\ldots\ldots\ldots\ldots \mathbf{Eq.\ 10}$$

Where LE is the loading efficiency (dimensionless) whose value ranges between 0 and 1 depending on the magnitude of the load borne by the solid matrix of the confined aquifer, σ is the total mechanical load which is the combined mass of overburden.

In the absence of vertical groundwater flow the expression becomes:

$$\mathbf{\frac{\partial p}{\partial t} = LE\frac{\partial \sigma}{\partial t}} \qquad \ldots\ldots\ldots\ldots\ldots \mathbf{Eq.\ 11}$$

LE, is related to compressibility by the following expression:

$$\mathbf{LE = \frac{\alpha}{n\beta + \alpha}} \qquad \ldots\ldots\ldots\ldots\ldots \mathbf{Eq.\ 12}$$

STUDY AREA

Climate and Hydrology

Bangladesh is a humid tropical country with great seasonal variability, receiving mean annual rainfall in access of 2300 mm (Islam et al., 2020). The eastern part of the country experiences comparatively higher annual rainfall than western part, up to 5000 mm (Fig. 2a) (Shamsudduha et al., 2011). Monsoon season is from May to October and Winter (dry) season is from November to April. Monthly evapotranspiration varies between 89 to 188 mm, being highest in April and May and with annual total of 1602 mm (BGS and DPHE, 2001). The country is crisscrossed by numerous rivers and their tributaries of variable nature which includes flashy, gentle and tidal rivers (Fig. 2b). Three major rivers i.e. the Ganges-Brahmaputa-Meghna, forming the second largest river system of the world, meet in the centre of the country and their combined flow discharges 1.35 x 10^{12} m^3/yr water to the Bay of Bengal. Annual river stage variations lie between ~2 to 12 m (Steckler et al., 2010).

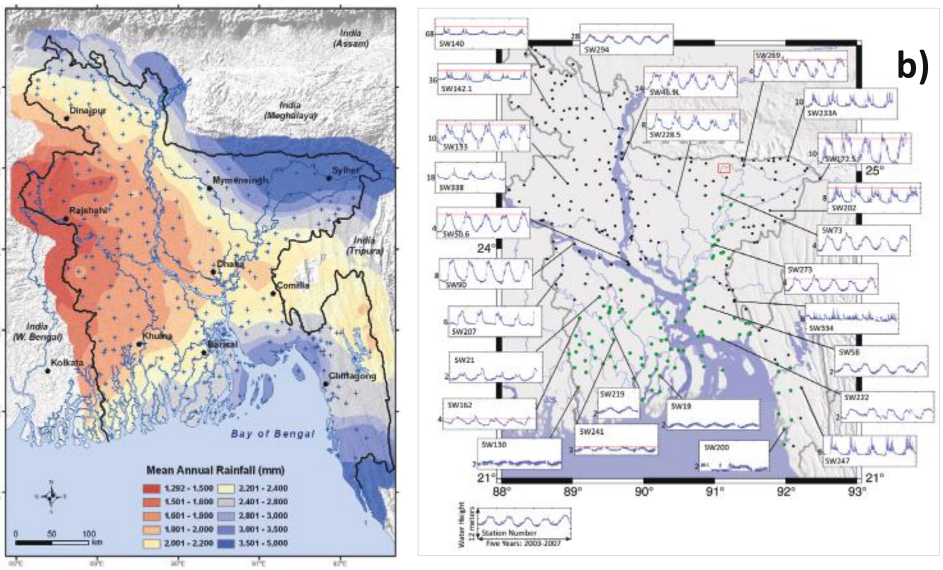


Figure 2: a) Spatial Mean Annual Rainfall in Bangladesh, after Shamsudduha (2011); b) Rivers of Bangladesh with River Gauging Stations Illustrating the Varied Patterns of Water Level Fluctuations, after Steckler et al., (2010)

Geology and Hydrogeology

The Bengal Basin, one of the largest sedimentary basins in the world is formed by sequences of fluvio-deltaic sediments of Late Cretaceous to Recent age (Burgess et al., 2010) derived from the erosion of the Himalayas and Indo-Burman mountains, having thickness of ≥16 km (Steckler et al., 2010) due to subsidence, sea level changes and associated fluvio-deltaic process (Goodbred and Kuehl 2000). This resulted in deposition of horizontally extensive but often discontinuous sequences of alternating fine and coarse grained sediments. The southern portion of the basin is dominated by fine-grained sediments largely of marine deposition and further inland relatively coarse-grained layers are found which are dominantly fluvial deposition. The Pleistocene terrace deposits (i.e. the Madhupur and Barind Tracts), are predominantly sands with silt and clay - generally brown-coloured, weathered, and more compacted than the Holocene floodplain and deltaic deposits that are generally gray-coloured, and composed of sand, silt, and clay with occasional peat deposits (BGS and DPHE, 2001).

BAS is a multi-layered, leaky aquifer system created by the unconsolidated to semi-consolidated fluvio-deltaic sediments of GBM floodplain of Plio-Pleistocene-Holocene age. Composite layers of clay, silt, sand, and gravel give the BAS a very heterogeneous architecture which is horizontally extensive, several hundred meters thick and is considered to overlie the basal hydraulic boundary drawn by the Upper Marine Shale of Mio-Pliocene age. A silt and clay sequence of variable thickness from <5 to 50 m exists across the GBM surface (Shamsudduha et al., 2011). Two principal aquifers are identified in BAS: the shallow aquifer (upper 80–100 m bgl) and the deep aquifer (>100 m bgl) are mentioned in the bulk of the literature on the hydrogeology of Bangladesh (BGS and DPHE, 2001). But the basis of their separation is not clearly defined due to non-existence of regionally extensive continuous confining units as shown by lithofacies analysis (Hoque and Burgess, 2020).

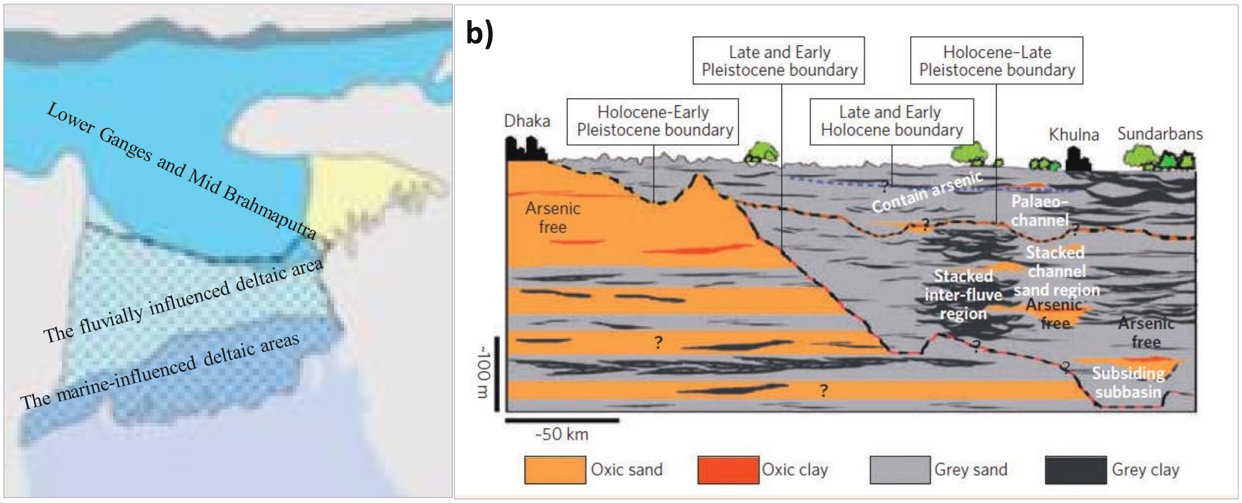


Figure 3: a) The Groundwater Typologies of Bengal Basin Extracted from IGB Basin, after Bonsor et al., (2017); b) Cartoon on Evolution of BAS after Burgess et al., (2010)

The aquifer beneath the Madhupur and Barind tracts is composed of brown sand and silt of the Dupi Tila formation of Plio-Pleistocene age, deposited in a fluvial setting and occurring at least to 250 m depth, and is free from arsenic (As). The aquifer beneath the active floodplains overlie Pleistocene sediments to a depth of about 100 m, and in the southern part of Bangladesh is mostly composed of grey sands, silts and silty clays of Holocene age (Ravenscroft et al., 2005) and is extensively contaminated with As. The aquifer in the southern part at greater depth is composed of belts of thick sands, and finer materials with limited lateral extents, (Goodbred and Kuehl, 2000) is arsenic-safe but occasionally is highly saline.

Aquifer properties may vary in different physiographic sub-regions, which is also reported in the typology mapping of the IGB- three typologies covering the Bangladesh part of (Bonsor et al., 2017) as in Figure 1.9a where hydraulic conductivity decreases and anisotropy ratio increases gradually from north to south. Hydraulic properties i.e. mean S of 0.0025 and

T of 1250 m^2/day for depths between ~200 m and ~300 m were determined in southern Bangladesh (BWDB, 2013) indicating confined to leaky-confined conditions (Zahid et al., 2017; Zahid et al., 2018).

Groundwater levels rise during the monsoon and fall during the dry-irrigation season in most parts of the country except the Barind Tract and Dhaka, where a continuously declining trend is clearly identified.

SOURCES OF HYDROLOGICAL LOADS

The Bengal basin, influenced by a monsoon-dominated tropical climate, is one of the world's most complicated and interactive hydrological systems (Debnath et al., 2019) and hosts the Bengal Aquifer System (BAS). It is a dynamic and highly seasonal hydrological system (Shamsudduha et al., 2012) as reflected by heavy monsoonal rainfall, a wide range of fluctuations in river stage including large tidal ranges, widespread flooding and frequent occurrence of storm surges. Each of these represents a source of variable mass loading on the aquifer system, which may potentially cause observable groundwater level fluctuations. High annual rainfall >2300 mm is an aerially extensive source of loading. Annual floodwater depth ranges from 0.3 to 11 m depending on the area where it occurs. Each year flood inundates on average one quarter of Bangladesh and an extreme flooding event inundates two thirds of the land area. The monsoon-season combined surface and groundwater load across the Bengal basin is ∼100 GT of water, and can be 150 GT during extreme flooding, which reflects the second largest seasonal anomaly in terrestrial water storage of the world as identified by the GRACE satellite mission (Steckler et al., 2010). In coastal areas, tidal rivers might be expected to be an important source of time-variant loading. There are mechanisms of unloading too during the dry season e.g. evaporation and evapotranspiration. The monthly evapotranspiration rate varies between 89 and 188 mm with the annual total of 1602 mm (BGS and DPHE, 2001).

EVIDENCES OF HYDRO-MECHANICAL BEHAVIOUR IN THE BAS

Evidence of Slow Groundwater Flow

The horizontally extensive Holocene-Pleistocene fluvio-deltaic aquifer sediments of several hundred meters thickness of the basin have a very low hydraulic gradient of ~0.0001 due to the low topographic relief (Burgess et al., 2002; Ravenscroft *et al.* 2005; Michael and Voss 2009a; Burgess et al., 2010), leading to slow lateral groundwater flow in the shallow aquifer with a Darcy velocity of ~ 2 m/year (Ravenscroft et al., 2005). Seasonal hydraulic head variations have minimal effect on the basin-scale flow paths spanning over thousands of years (Michael and Voss, 2009a), The vertical hydraulic conductivity is also very low and the aquifer anisotropy (K_h/K_v) is very high, estimated to be between 10^3 (Hoque and Burgess, 2012) and 10^4 (Michael and Voss, 2009a). This effective vertical anisotropy together with the ubiquitous presence of discontinuous silty clay layers in the aquifer system effectively restricts vertical groundwater flow (Michael and Voss, 2009a; Hoque et al., 2017).

The confined to leaky-confined nature of deep groundwater as reflected in the S value (avg 0.0025) is markedly differentiated from shallow groundwater, with S_y values for the shallow aquifer that range from <0.05 to 0.2 (Bonsor et al., 2017).

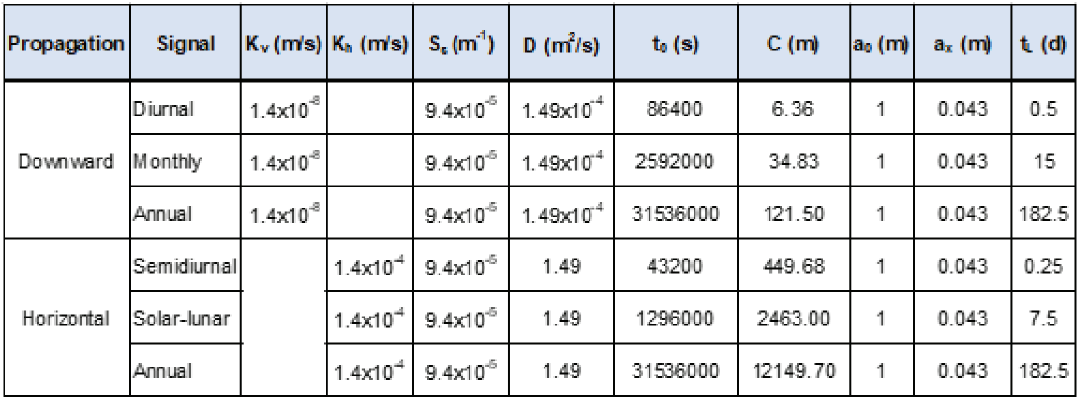
Evidence of Minimal Hydraulic Interaction between Shallow and Deep Groundwater

Deep groundwater is found to contrast with the shallow groundwater as it is often free of arsenic and has a distinct isotopic signature in Matlab and Araihazar Upazilas (von Brömssen et al., 2014; Bhattacharya et al., 2016; Mihajlov et al., 2016). There is no recent recharge to deep groundwater, which is aged >3 Ka, and there is no regional or aquifer scale contamination as revealed from age depth-profiles and by tracer studies in coastal Bengal Basin (Lapworth et al., 2018), However, relatively younger (<2 Ka), high-arsenic deep groundwater in the areas which lack a low permeability layer in south-western Bengal Basin has been reported in a modeling study (Khan et al., 2019). This hydrochemical evidence supports a minimal hydraulic interaction between deep and shallow groundwater.

Evidence of Low Hydraulic Propagation of Surface Signals

Hydraulic effects of daily variations in surface water depth above the confined aquifer in the Bengal basin are not expected to propagate beyond 10 m depth with a time lag of 0.5 day; monthly signals are not expected to propagate beyond 30 m (Burgess et al., 2017) with a time lag of 15 days. The 1 m amplitude of the annual hydraulic signal would decrease to cm scale at 120 m depth with a lime lag of ~180 days (Eqs. 2, 3 and 5) (Table 1). This analysis shows that an un-attenuated and immediate water level response at depth >C (propagation depth) can be considered as the mechanical response to hydrological loading signals of shallow origin at a range of frequencies. Similarly, accounting for anisotropy ($K_h/K_v=10^4$), a sub-daily hydraulic signal from a surface water source (e.g. river) is not expected to travel more than 500 m lateral distance with a time lag of 0.25 day, a lunar monthly (15 days) signal is not expected to travel more than 2500 m with a time lag of 7.5 days, and an annual signal is not expected to travel more than 12000 m with a lime lag of ~180 days (Eqs. 2, 3 and 5) (Table 1). These computations indicate that a response not sufficiently attenuated at distance >C (propagation distance) and also not sufficiently lagged, can be considered as the mechanical response to hydrological loading signals of a range of frequencies and distances from the source.

Table 1: Downward and Lateral Propagation of Hydraulic Signal in the BAS Showing the Amplitude Decay with Depth and Distance and Their Associated Time Lags



Propagation	Signal	K_v (m/s)	K_h (m/s)	S_s (m^{-1})	D (m^2/s)	t_0 (s)	C (m)	a_0 (m)	a_x (m)	t_L (d)
Downward	Diurnal	$1.4x10^{-8}$		$9.4x10^{-5}$	$1.49x10^{-4}$	86400	6.36	1	0.043	0.5
	Monthly	$1.4x10^{-8}$		$9.4x10^{-5}$	$1.49x10^{-4}$	2592000	34.83	1	0.043	15
	Annual	$1.4x10^{-8}$		$9.4x10^{-5}$	$1.49x10^{-4}$	31536000	121.50	1	0.043	182.5
Horizontal	Semidiurnal		$1.4x10^{-4}$	$9.4x10^{-5}$	1.49	43200	449.68	1	0.043	0.25
	Solar-lunar		$1.4x10^{-4}$	$9.4x10^{-5}$	1.49	1296000	2463.00	1	0.043	7.5
	Annual		$1.4x10^{-4}$	$9.4x10^{-5}$	1.49	31536000	12149.70	1	0.043	182.5

In this table K_v and S_s value are from (Michael and Voss 2009a) and K_h is taken accounting for anisotropy. Note that t_0 is the period, a_x is the amplitude of the hydraulic signal at C (propagation depth/distance), and t_L is time lag.

Evidence of Highly Compressible Sediments and High Loading Efficiency (LE)

Four indirect estimates of sediment compressibility (α) may be extracted from analyses at borehole scale (Burgess et al., 2017) and basin scale, (Michael and Voss, 2009a), (Steckler et al., 2010) and (Woodman et al., 2019). A value of about 10^{-10} Pa^{-1} is derived using Eq. 8, from the Young's Modulus (E) estimated for sediments in the upper few kilometers (Steckler et al., 2010), a value of about 9.4 x1 0^{-9} Pa^{-1} from the specific storage (S_S) using Eq. 9 estimated in basin scale modelling study for BAS (Michael and Voss, 2009a) and value between 2.6 $x10^{-10}$ Pa^{-1} and 1.1 $x10^{-7}$ Pa^{-1} for α has been derived from the Loading Efficiency (LE) estimated by Burgess et al., (2017) and Woodman et al., (2019) (Table 2). These estimates are close, and fall in the range of values determined by Smith et al. (2013) for a thick claystone aquitard of Cretaceous age, which are 2 to 4 orders of magnitude less than the value for sediments reported in textbooks (Domenico and Schwartz, 1998). Some ranges of values of S_S and E have been used in order to approach the textbook value, presented in the Table 2 (gray shade).

The estimated sediment compressibility (α) values and their corresponding higher loading efficiency (LE) values in BAS may be attributed by relatively younger unconsolidated thick heterogeneous Holocene sediments both spatially and vertically which have not been consolidated and carries the hydrological loads. Therefore, the sediments of Bengal basin can be considered as highly compressible, having high value of S_S (Michael and Voss, 2009a).

Evidence of Rainfall Loading and River Loading

Rainfall loading has strong influences on groundwater pressure under confined conditions of BAS, by driving the immediate responses seen in vertically stacked piezometers with the first evidence reported in an inland site in Bangladesh (Burgess *et al.* 2017) (Fig. 4a). Tidal loading influences on groundwater head in the coastal region is demonstrated by nearly synchronous responses in the groundwater head time series at a site in south-west Bangladesh (Fig. 4b) (Burgess *et al.* 2017). Also there is evidence of groundwater heads responding to river loading in southern Bangladesh, close to Khulna (the Rupsa river) (Woodman *et al.* 2019) and in Matlab (the Meghna river) (Sultana *et al.* 2019).

Table 2: Estimation of Sediment Compressibility (α) from Young's Modulus (E), Specific Storage (S_S) and Loading Efficiency (LE)

	E (GPa)	**α (Pa^{-1})**	**LE**	**Comments**
Eq. 8	10	$1x10^{-10}$	0.455	E value is 10 GPa (Steckler et al. 2013) high enough to reach textbook value of α determined for plastic clay to dense sandy gravel ie 10^{-6} to 10^{-9} Pa^{-1} (Domenico & Schwartz, 1998) but can be achieved if E ranges from 0.01 GPa to <1 GPa and corresponding LE ranges from 0.988 to 0.999 (grey shaded)
	1	$1x10^{-9}$	0.893	
	0.1	$1x10^{-8}$	0.988	
	0.01	$1x10^{-7}$	0.999	
	S_s (m^{-1})	**α (Pa^{-1})**	**LE**	**Comments**
Eq. 9	$1x10^{-2}$	$1.0x10^{-6}$	1.000	S_s is $9.4x10^{-5}$ m^{-1} for BAS (Michael & Voss, 2009) and it ranges from 10^{-2} to 10^{-5} m^{-1} for plastic clay to dense sandy gravel in textbook (Domenico & Schwartz, 1998). Textbook value of α can be achieved for plastic clay to dense sandy gravel if S_s ranges from 10^{-2} to 10^{-4} m^{-1} and corresponding LE ranges from 0.988 to 1 (grey shaded)
	$1x10^{-3}$	$1.0x10^{-7}$	0.990	
	$1x10^{-4}$	$1.0x10^{-8}$	0.988	
	$1x10^{-5}$	$9.0x10^{-10}$	0.882	
	$9.4x10^{-5}$	$9.4x10^{-9}$	0.987	
		α (Pa^{-1})	**LE**	**Comments**
Eq. 12		$2.6x10^{-10}$	0.69	LE ranges 0.69-0.87 for BAS (Burgess et al. 2017) small enough to reach textbook value of α determined for plastic clay to dense sandy gravel i.e. 10^{-6} to 10^{-9} Pa^{-1} (Domenico & Schwartz, 1998) but LE ~ 1 (Woodman et.al. 2019) (grey shaded) makes α fall within plastic clay and stiff clay (10^{-7} Pa^{-1}) conforming textbook value.
		$8.0x10^{-10}$	0.87	
		$1.0x10^{-9}$	0.9	
		$1.1x10^{-7}$	0.999	

Note that β is taken ($4.8x10^{-10}$ Pa^{-1}) at 25^0C and n is taken 0.25.

Evidence from Vertical Component of GPS Data

Seasonal vertical elastic deformation of the crust has been detected at 25 sites across Bangladesh by continuous GPS monitoring (Steckler et al., 2010; Steckler et al., 2013). Seasonal oscillation of 50-60 mm of the ground surface has been observed due to elastic deformation and rebound of the delta under the increasing and decreasing combined load of surface water and ground water (>100 GT) corresponding to annual wet and dry periods (Fig. 5) (Higgins et al., 2014).

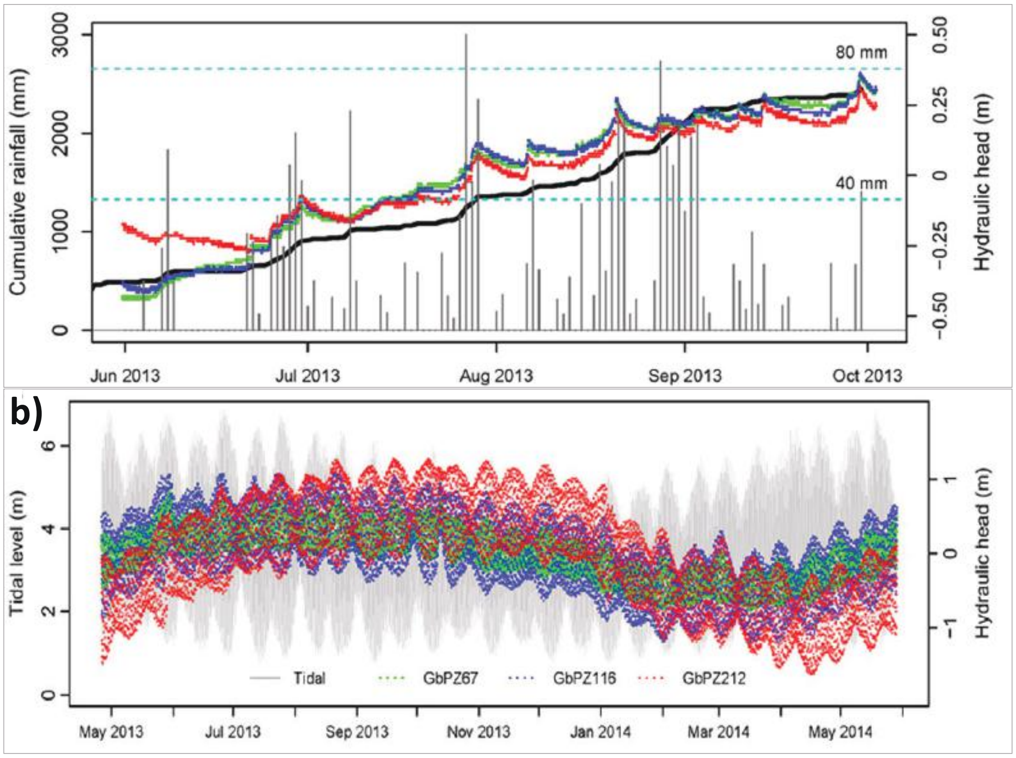


Figure 4: a) Response of Groundwater Head of Three Different Depths to Daily Rainfall at Laksmipur, Bangladesh; b) Hydraulic Heads from Three Different Depths and Tide Level at Gabura, Bangladesh, after Burgess et al., (2017)

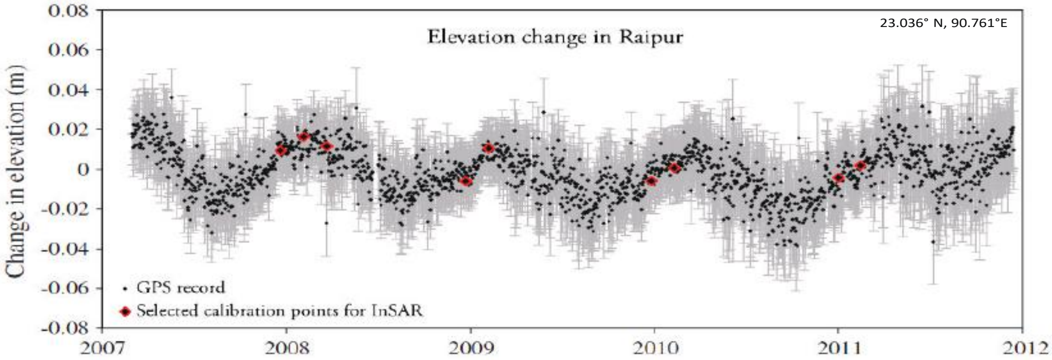


Figure 5: Time Series Plot of Vertical GPS Recording from Raipur City (RPUR) Showing Changes of Surface Elevation Synchronous with Monsoon as a Result of Elastic Deformation and Rebound of the Area Due to Loading and Unloading of Surface Waters Corresponding to Wet and Dry Periods after Higgins et al., (2014)

CONCLUSIONS

To summarize, the low topography, the existence of a top silty clay layer over a thick heterogeneous sedimentary aquifer having high anisotropy, with restricted vertical flow, high sediment compressibility and low propagation depth of hydraulic signals, allow BAS to behave hydro-mechanically. This behaviour has been identified using high frequency groundwater pressure data (Burgess et al., 2017), predictively mentioned in deep groundwater (Ravenscroft et al., 2018) and investigated through partially coupled hydro-mechanical modeling (Woodman et al., 2019), with provisional observations at proximal river sites (Sultana et al., 2019).

The review provides useful insights of surface loading which has significance for groundwater resource management in Bangladesh and are applicable to similar environments i.e., other fluvio-deltaic aquifers across the world. Therefore, it is important for a wide spectrum of interests with a common requirement to correctly interpret groundwater hydrographs.

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