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Subsidence and human influences in mega deltas: The case of the Ganges–Brahmaputra–Meghna

S. Brown *, R.J. Nicholls

Faculty of Engineering and the Environment, University of Southampton, Highfield, Southampton, SO17 1BJ, United Kingdom
Tyndall Centre for Climate Change Research, United Kingdom

HIGHLIGHTS

- Reported subsidence rates are variable: A mean of 5.6 mm/yr, and median of 2.9 mm/yr.
- Highest rates occurred in the last 1000 years, with a mean of 8.8 mm/yr.
- Rates are affected by measurement method; improved monitoring is required.
- Land use changes can affect net subsidence leading to environmental degradation.
- Limited knowledge of subsidence can hinder management responses.

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ABSTRACT

Relative sea/land level changes are fundamental to people living in deltas. Net subsidence is complex and attributed to tectonics, compaction, sedimentation and anthropogenic causes. It can have severe impacts and needs to be quantified and where possible (for subsidence due to anthropogenic causes) avoided. For the highly populated Ganges–Brahmaputra–Meghna delta, a large range of net subsidence rates are described in the literature, yet the reasons behind this wide range of values are poorly understood. This paper documents and analyses rates of subsidence (for publications until 2014) and relates these findings to human influences (development).

205 point measurements of net subsidence were found, reported in 24 studies. Reported measurements were often repetitive in multiple journals, with some lacking detail as to precise location, cause and method, questioning reliability of the rate of subsidence. Rates differed by locality, methodology and period of measurement. Ten different measurement methods were recorded, with radio-carbon dating being the most common. Temporal and spatially, rates varied between −1.1 mm/yr (i.e. uplift) and 43.8 mm/yr. The overall mean reported rate was 5.6 mm/yr, and the overall median 2.9 mm/yr, with 7.3 mm/yr representing one standard deviation. These rates were reduced if inaccurate or vague records were omitted. The highest rates were recorded in the Sylhet Plateau, Dhaka and Kolkata. Highest rates were recorded in the last 1000 years, where the mean increased to 8.8 mm/yr and a standard deviation of 7.5 mm/yr. This could be partly due to shorter-term measurement records, or anthropogenic influence as multiple high rates are often found in urban settings. Continued development may cause rates to locally increase (e.g. due to groundwater abstraction and/or drainage). Improved monitoring is required over a wider area, to determine long-term trends, particularly as short-term records are highly variable. Focus in regions where wide spread development is occurring or is expected would be advantageous.

1. Introduction

Deltas are important dynamic environments that are constantly reshaped and reformed. Worldwide, they are home to hundreds of millions of people, including many large and growing cities. They contain intense ecosystem services and economic activities that support these populations and often rapid economic growth. Environmental change is widespread including in the catchments and the deltas themselves (e.g. through reservoir creation, dredging and channelling to control water availability or reduce flood risk). In many places world-wide, environmental change is recognised, but it can still catch people by surprise. This was recognised in the aftermath of Hurricane Katrina over New Orleans, USA (2005), where it was found that local land levels had subsided by more than 1 m since the upgrade of dikes after

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Abbreviations: GPS, Differential Geographical Positioning System; GRACE, Gravity Recovery and Climate Experiment; InSAR, Interferometric Synthetic Aperture Radar.

* Corresponding author.

E-mail address: sb20@soton.ac.uk (S. Brown).

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Hurricane Betsy in the 1960s, making them ineffective against the extreme water levels during Katrina (Dixon et al., 2006). Although the delta was known to be subsiding, the detail on the ground was poorly recorded with little systematic monitoring and analysis.

Subsidence is the norm in deltas, and is caused by a multitude of natural processes, which are often augmented by anthropogenic reasons. This includes tectonics, changes in erosional control on a river or coast, sediment compaction, changes in farming practices (e.g. irrigation), deforestation, mining, groundwater or hydrocarbon extraction and changes to coastal management, such as levees or embankments (Ericson et al., 2006; Syvitski, 2008). Together these factors can result in ground subsidence or uplift/rising land, or more commonly a combination of the two (Fig. 1). Net subsidence is the combined affect of land sinking and land rising, including sedimentation. Subsidence can result in increased flooding and subsequent shoreline retreat and land loss. It can reduce the efficiency of defences, and increase salinisation, affecting agriculture, having the potential to affect millions of people, many who may be in poverty (Syvitski, 2008; Syvitski et al., 2009). Rising sea levels causes similar effects, and these processes reinforce each other.

One important delta where subsidence is poorly understood is the Ganges–Brahmaputra–Meghna (GBM) basin in south-east Asia (Fig. 2). The delta is the second largest in the world by area, containing more than 100 million people (Ericson et al., 2006). Numerous values of subsidence are reported in the literature, ranging from −1.1 mm/yr (i.e. land up-lift) (Hoque and Alam, 1997) to 41 mm/yr (Morgan and McIntire, 1959), most of which could be justifiably cited, but would not necessarily be representative or meaningful of the delta behaviour. With such a wide range of subsidence rates reported (both temporally and spatially), it is important to understand present and future subsidence and how it could interact with other changes. This is particularly important as in the GBM delta there have been widespread concerns over the adverse effects of climate, human and other physical changes in the delta dating back nearly 30 years (Broadus et al., 1986; Milliman et al., 1989). This presents challenges in a country such as Bangladesh and the West Bengal region of India. Funding and resources are limited, and thus monitoring and data (particularly that is publically available) are scarce. Hence the aim of this paper is to take the GBM delta as follows: (1) review natural and anthropogenic influences of subsidence; (2) identify causes of land-based subsidence in the basin, in particular the delta region; (3) synthesise available subsidence data and methods; and (4) discuss the wider developmental and environmental implications.

This paper has not generated new values of subsidence, or undertaken a detailed study of the causes and processes of subsidence. Rather it assesses and synthesises the large body of published data, including the grey literature. Many studies which use or describe rates of subsidence are selective as to the ones which they report, and do not always take account of the quality or range of data available. Furthermore, there is no published assessment synthesising all values known to the authors. Present data range from satellite measurements (e.g. Higgins et al., 2014), field explorations (e.g. Goodbred and Kuehl, 2000a) to hand-drawn sketches (e.g. Master Plan Organisation, 1985 as cited in Singh et al., 2000). Due to the scattered nature of the data, some data resources have not been seen by the authors' first-hand, and thus are cited from the primary text (see Supplementary Material).

2. Setting

2.1. Natural aspects

The GBM basin, at 1.7 million km^2 (Allison, 1998a) covers six countries — Bangladesh, Bhutan, China, India, Myanmar and Nepal (Fig. 2). The delta, situated in Bangladesh and India (West Bengal), covers approximately 100,000 km^2 of lowland flood and delta plains (Goodbred and Kuehl, 2000a). The delta front is around 380 km long (Allison, 1998a). Many parts of the tidal influenced delta are less than 3 m above mean sea level and with the tidal influence extending up to 100 km inland, around one quarter of Bangladesh can be considered

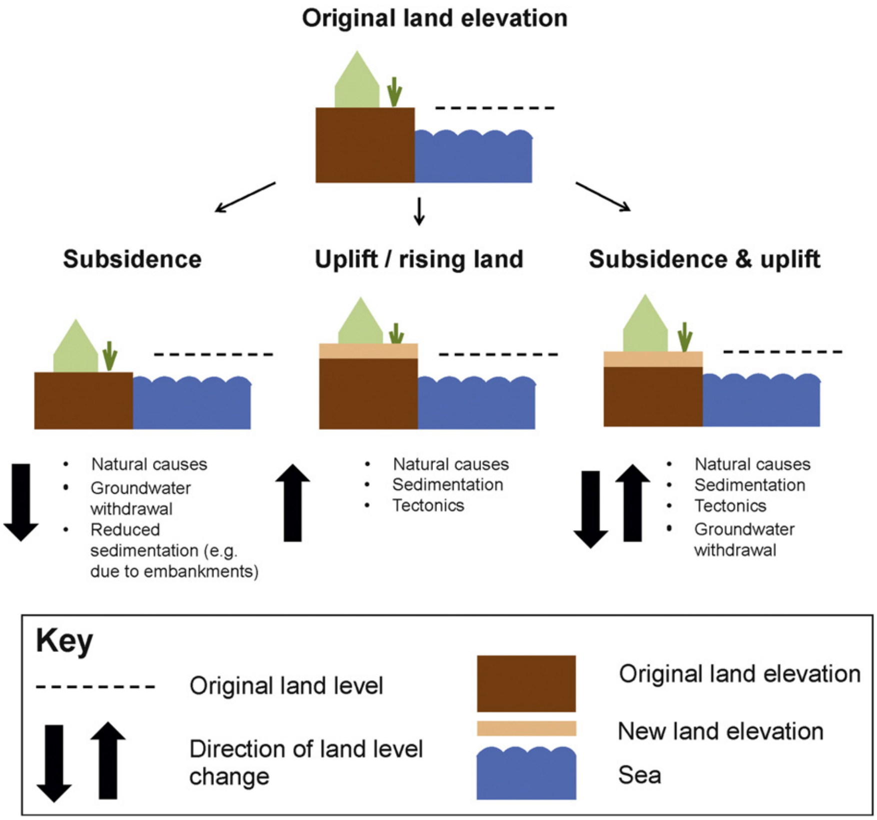

Fig. 1. Potential examples of how land elevation changes over time due to land uplift and subsidence.

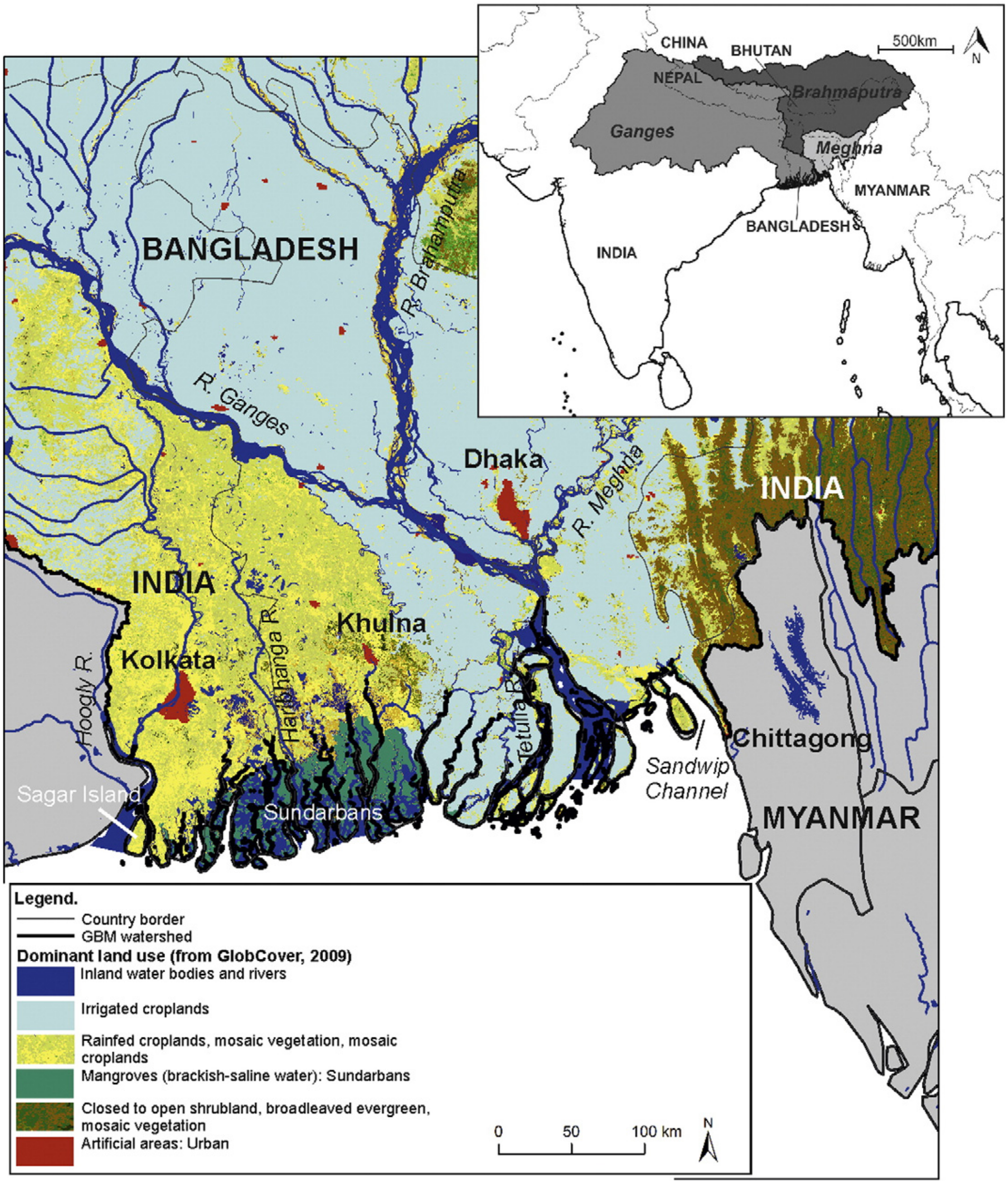

Fig. 2. Geographical setting of the Ganges–Brahmaputra–Meghna basin and delta, including dominant land use. Base map data taken from: DIVA-GIS (2014), GADM (2012), GlobCover (2009) and Pacific Disaster Center (2000). Inset: The basin's regional setting. Basin outlines provided by IIT Kanpur.

'coastal' (Kausher et al., 1996). The combined seasonal discharge (peaking during the May to November monsoon season) of the Ganges–Brahmaputra river system outputs approximately 1 billion tonnes of sediment per annum, and accounts for approximately 10% of the world's sediment output from rivers to the ocean (Milliman and Meade, 1983; Syvitski et al., 2005; Milliman and Farnsworth, 2011). However, there are some areas of the delta where sediment supply is not sufficient to offset subsidence or erosion, so are at risk from flooding and erosion, namely the Sylhet Basin, the Indian tidal delta plain and the fluvio-tidal transition in the western and central parts of the delta (Wilson and Goodbred, 2015). Where sediment is deposited en route to the sea and at the mouth of the delta, new small, river islands are created called chars. Chars and the river banks are in a state of flux, being shaped and reworked by river and oceanographic processes, including tides which have a range of up to 4 m–5 m. Rates of net land accumulation in the river mouth are reported to extend land area by up to 7 km^2/yr (1792–1984) (Allison, 1998b). In the western delta, erosion (particularly during extreme events, such as Cyclone Sidr in 2007) can be up to 20 m/yr (1989–2009) (Sarwar and Woodroffe, 2013). Overall in the Bangladeshi part of the delta, data since the 1980s indicates there has been a slight net gain of land (Brammer, 2014; Sarwar and Woodroffe, 2013), whereas in the Sundarbans mangroves, a net loss has been reported (Shearman et al., 2013).

The basin's geology is shaped by complex active faulting, stemming from the collisions of the continental plates containing India and Asia during the mid-Oligocene (23–34 Ma BP), and subsequent formation of the Bengal Basin (Allison, 1998b). The Comilla Terrace is an uplifting region, underlain by buried folds, whilst the Madhupur Tract was uplifted in the Pleistocene which tilts towards the east and is potentially faulted towards the west (Steckler et al. 2008a) (Fig. 3). Sediment is thickening towards the east and Indo-Burma belt, due to subduction (Uddin and Lundberg, 2004). Almost all of the foredeep is filled with fluvio-deltaic sediment and alluvium from the Ganges–Brahmaputra river system deposited in the last 66 million years and is up to 16 km

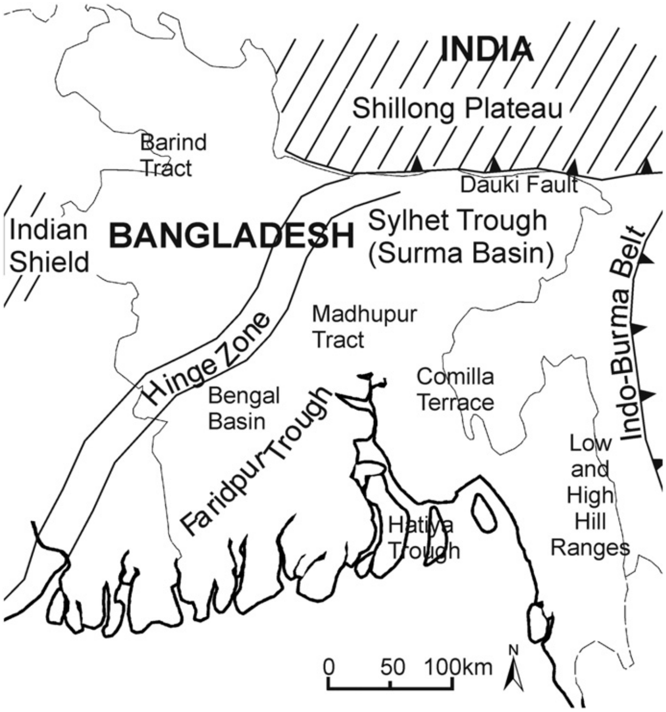

Fig. 3. Geology of the Ganges–Brahmaputra–Meghna basin.
Based on Hoque and Alam (1997) Goodbred and Kuehl (2000a), Johnson and Alam (1991), Steckler et al. 2008a and others.

thick (Allison, 1998a). The Holocene deposits (from 11,700 years BP) are estimated to be 30 m to 70 m thick in the deltaic plains and include stiff clays, mud, silt, sand and peats (Khan and Islam, 2008).

2.2. Anthropogenic aspects

Human settlement has occurred for thousands of years. More recently, settlements grew and were influenced by trade, ports and shipping. Kolkata become a major port, partly under European influence over the last few hundred years (van Schendel, 2009). As the general regional population expanded by the late 18th century, dikes and dams were required to hold back flood water from the river, prevent salinisation and provide agricultural lands, via conversion from mangroves (Islam, 2006; Kausher et al., 1996). Management intensified in the late 19th century where landlords continued to build and improve upon small embankments. In 1948 the delta was split between two countries: India and East Pakistan (now Bangladesh). Significant impacts to control river flow and reduce salinity intrusion were not made until the 1960s when the Coastal Embankment Project in what is now Bangladesh initiated the building of a larger, planned network of earthen embankments (Kausher et al., 1996). Funded by the World Bank and other organisations, the aim was to create land to satisfy agricultural production for the growing population, and hence to increase well being. The land was polderised and drained. However, by the 1990s, adverse effects were noted, including drainage congestion inside and heavy siltation outside of the polders in south-west Bangladesh. This made some of the land unsuitable for agriculture (Islam, 2006). A lack of siltation on the delta plain due to embankments, compounded by subsidence, meant that land levels lowered (Fig. 4). For example, Auerbach et al. (2015) found that after five decades of polderisation, the difference in height between natural and artificial landscapes equated to approximately a metre, or an average 2 cm/yr. This is an order of magnitude greater than global sea-level rise over this period (c.f. Church et al., 2013). Today, remedial projects have tried to better facilitate the coastal zone and its land use policies (Islam, 2006), most recently by the World Bank Coastal Embankment Improvement Program (World Bank, 2015).

2.3. Land use

To understand the implications of subsidence in this review, the delta and surrounding area was divided into five dominant land use categories, extracted from GlobCover (2009). GlobCover (2009) was generated from the ENVISAT MERIS satellite data from January 2005 to June 2006 and represents 22 major land use classes. Whilst recognising that 100% accuracy of land cover cannot be achieved, the data which is

Fig. 4. Subsidence and reduced sedimentation due to embankment construction has led to river levels being higher than adjacent land levels in the Sundarbans, West Bengal, India, reinforcing that subsidence can have local causes.
Courtesy of Attila Lázár (taken January 2014).

reported at 300 m resolution was validated by experts. The dominant land use categories were: (1) Irrigated croplands; (2) rainfed croplands, mosaic croplands, and mosaic vegetation; (3) mangroves (brackish-salty water) (mainly the Sundarbans); (4) closed to open shrubland, broadleaved evergreen, and mosaic vegetation; and (5) artificial areas: (mainly urban). These are shown in Fig. 2. In the west of the delta, rainfed croplands are the dominant land type, with Kolkata the largest growing city. Rainfed croplands are also present immediately north and west of the Sandwip Channel. On the coast, the Sundarban mangrove forests lie up to 2.1 m above mean sea-level. Following a period of destruction, mangroves have been replanted and managed, which has helped to converse, stabilise and encourage accretion of new land (Iftekhar and Islam, 2004). On the coast, tidal flats, natural leeves and tidal creeks are present. East of Khulna, the land use type shifts to irrigated croplands in a river-dominated, fluvio-tidal and tidal-dominated landscape. This landscape has been altered through the Coastal Embankment Project, where cross dams (embankments across tidal channels) blocked water flow encouraging infilling of sediment and the creation of land. As a consequence, river flow changed and locally enhanced erosion (Kausher et al., 1996). Additionally areas downstream of the 1975 Farakka Barrage were affected due to the retention of sediment and changes in water movement and tides, although the effects of this remain difficult to quantify (Allison, 1998a; Kausher et al., 1996).

3. Causes and quantification of changes in land elevation

3.1. Causes

In deltas, land elevation can rise or fall, leading to net subsidence. Four main mechanisms are apparent in the GBM delta: (1) tectonic subsidence/uplift (including neotectonics); (2) compaction of sediment or peat (subsidence); (3) anthropogenic subsidence, such as fluid extraction, drainage, embankment building; and (4) sedimentation (i.e. accretion or elevation gain) (Hoque and Alam, 1997; Syvitski, 2008). In geological time, plate-driven tectonic processes rather than compaction, are believed to be the main source of subsidence, particularly in the Faridpur and Hatiya Troughs in the lower delta (Goodbred and Kuehl, 2000a; Hoque and Alam, 1997). However, more recently, compaction has become increasingly important. Relative land level change is further complicated by sedimentation. Some causes of subsidence are very local (scale of tens or hundreds of square metres) and occur over short time scales (e.g. water abstraction, embankment building and resulting loading over a decadal scale). Others occur over a wide area at a slower, more uniform rate (e.g. neotectonic processes over thousands of years or more). Due to multiple causes of subsidence and a general lack of monitoring, particularly in remote locations, understanding the causes and patterns of subsidence is challenging.

3.2. Study methodology

To create a database of subsidence, a literature review was undertaken (for publications up to 2014) noting the data source(s), location, rate, age and methodology (see Supplementary Material noting these parameters). To gain the widest perspective possible, all rates were noted in the database, regardless of the source or perceived data quality. Locations mentioned in journal articles were at times precise, narrowing down to a village or small harbour (e.g. Port Canning or Gawonia, where the latter also has a latitude and longitude), but others were rather vague (e.g. Sundarbans or Faridpur Trough). In the latter cases, a general latitude and longitude was selected in the middle of that region. The only exception to point data, was a 10,000 km^2 region of Interferometric Synthetic Aperture Radar (InSAR) data (spatial resolution 100 m) generated by Higgins et al. (2014) covering a region of irrigated cropland surrounding Dhaka.

A total of eleven measurement methods were found in the literature: archaeological, borings/well logs/auger, carbon dating (augmented with optically stimulated luminescence in Hanebuth et al. (2013)), geomorphic surveys, differential Geographical Positing System (GPS), gravity surveys, groundwater levels, InSAR, neotectonics, magnetostratigraphic dating, and tank excavations. Historical evidence for subsidence (and uplift) can be recorded by neotectonic activities via isostatic loading, faulting, tilting, gravity anomalies, earthquakes and changes in river course (Goodbred and Kuehl, 2000a; Hoque and Alam, 1997), with some measurements recording subsidence prior to the Holocene. Subsidence can also be seen from freshwater logs, borings, tank excavations and vegetation buried under ground surfaces and in coastal agriculture land. Radiocarbon dating is a popular method via collecting samples of wood, peat, organic material or human artefacts, and are commonly considers Holocene change. Rates of land level change can also be determined indirectly through well logs or from old buildings or ancient temples (some several hundred years old). Hoque and Alam (1997) report that in the older parts of Dhaka city, floors which were initially built at ground levels, are now ‘a few feet below the land surface’. More recent evidence is witnessed through local groundwater levels. Present day subsidence can also be measured by a GPS, magnetostratigraphic dating and geomorphic surveys.

The range of methodologies are described in Table 1 (excluding gravity surveys as the source data did not describe the methodology), along with the advantages and disadvantages for each method. A range of methods provides greater confidence in results, as each indicates different sensitivities and origins of subsidence. For 14% of the measurements from the point data records, the method is not known. From the remaining data, 37% of subsidence measurements are from radiocarbon dating, 19% from groundwater levels (in Kolkata), 14% from borings, well logs or augers and 9% from neotectonics (including measurements with a combination of methods). A disadvantage of many of the measurement methods is that they only record subsidence at one location, and one point in time, rather than being integrated over various time periods and spatial areas. Given that the causes of subsidence can be highly localised and occur at varying depths, this can create a biased view, particularly where there may be an intention to measure high rates where visual changes can be seen. GPS and InSAR are two advantageous and emerging methods of measuring subsidence, which over a period of decades will potentially grow into a very useful resource, such as gaining a better understanding of seasonal changes, or possible reverses in land motion (e.g. at Raipur, as reported in Higgins et al., 2014).

3.3. Results

Subsidence rates are reported over the whole delta, regionally and at specific locations. For the whole delta, Ericson et al. (2006) reported a rate of up to 10 mm/yr (no time period defined). Regionally, Khan and Islam (2008) stated 3 mm/yr for the lower delta (no time period defined); and Schiermeier (2014) reported up to 9 mm/yr of subsidence in the western delta, and up to 4 mm/yr in the east (precise locations and age not given, but based on recent GPS data (see Steckler et al., 2010 for a similar study)). Additionally, Ostanciaux et al. (2012) reports subsidence values between 12.3 mm/yr (in the western delta) to uplift of 3.6 mm/yr (in the eastern delta) (during an unspecified period between 1993 and 2009). Using InSAR measurements, Higgins et al. (2014) raw data records are between 15.7 mm/yr uplift to 49.4 mm/yr subsidence over a four-year period, although in discussion they suggest broad subsidence rates are up to 18 mm/yr (but this does not take account of active sedimentation). Offshore, on the outer Bengal Shelf (approximately 100 km to 150 km offshore), subsidence has been measured by Hübscher and Spieß (2005) and others, who record 0.4 mm/yr of subsidence over the last 345,000 years.

In addition, 205 references (of point measurements) for named geographical locations were found in the literature from 24 author teams (Fig. 5). These were: Alam (1996), Allison et al. (2003), Bhattacharya et al. (2004), Brammer (2014), Chatterjee et al. (2006, 2007), Ganguli

Table 1
Descriptions, advantages and disadvantages of methods employed to measure subsidence, excluding gravity surveys as no information was provided in the source material. Many comments sourced from papers citing subsidence records (see Supplementary Material).

Method	Description	Advantages	Disadvantages
Archaeological	Height measurements of temples or old buildings.	Often a definite date. Quick and easy to measure. Little expertise required.	Can be unclear whether accretion or subsidence, or both.
Borings/well/auger	Cylindrical sample of strata.	Can see sediments and better understand geophysical processes and cause of subsidence. Easy to obtain.	Unclear of age, which at times has beenassumed by the author, which may be misleading. Potential field access and equipment. Unclear whether buried due to subsidence or active sedimentation.
Carbon dating	Decay of unstable isotope carbon-14.	Number of samples. Straightforward, accessible testing. Can be compared with optical stimulated luminescence dating.	Age limitation. Potential contamination. Variations in carbon ratio. Unclear whether buried due to subsidence or active sedimentation.
Geomorphic survey	Landscape measurements.	Quick, easy to measure. Due to scale, source of subsidence may be visually clear.	Observations may tend to large-scale subsidence only, skewing results. Unclear what other processes may have occurred resulting in a similar effect.
GPS	Differential measurements using satellite signals with millimetre precision.	Precise measurements. Potential for long-term surveying, but presently only short-term records.	Expensive equipment. Areas at risk identified by the Gravity Recovery and Climate Experiment (GRACE) satellite via water storage. Expert knowledge and maintenance of GPS stations required. Only recent past. At present, insufficient data to gauge longer-term trends. Difficulty in accessing remote locations. Cannot record active sedimentation.
Groundwater levels	Changes in water level based on geotechnical theory and piezometric levels of cohesive soils.	Precision of locations. Ability to determine short-term variations, such as through a monsoon season.	Only short term measurements recorded, some subject to assumptions and/or large errors. Local knowledge required.
InSAR measurements	Post-processed satellite data measuring digital elevation.	Precise measurements that may be used over wide, inaccessible regions. Helps gain a broader understanding of processes of cause and effect.	Only measures vertical motion, not direct surface changes, such as sedimentation, leading to a partial measurement of relative land level change. Expensive, requiring expert knowledge.
Neotectonics	Observations and measurements.	Potentially very long records.	Remoteness of locations. Local geological knowledge.
Magnetostratigraphic dating	Determined from paleomagnetic polarities from sediment sample collection.	Potentially very long records. Can be highly sensitive.	Quality depends on sedimentation rates, reversals or other age determinants. Fragile samples. Remoteness of locations. Cost.
Tank excavation	Uncovering of sediments by equipment or machinery.	Can see sediments and better understand geophysical processes and cause of subsidence.	Use of equipment, maybe challenging in remote locations. Dates can be unclear, or assumed by the author. Unclear whether buried due to subsidence or active sedimentation.

(2011), Goodbred and Kuehl (2000a), Hanebuth et al. (2013), Hazra et al. (2001), Higgins et al. (2014), Hoque and Alam (1997), Islam et al. (1999), Johnson and Alam (1991), Khan and Islam (2008), Morgan and McIntire (1959), Pethick and Orford (2013), Sahu and Sikdar (2011), Sarker et al. (2012), Stanley and Hait (2000), Steckler et al. 2008b, Steckler et al. (2010), Warrick et al. (1996), and Worm et al. (1998). Many of these records did not have primary data, but cited (rightly or wrongly) earlier sources. In total, they cited an additional 22 articles. A summary is shown in Table 2, with full references available in the Supplementary Material and kmz file.

Results indicate an overall mean rate, taking account of all spatial and temporal point measurements of 5.6 mm/yr and a median rate of 2.9 mm/yr, with a standard deviation of 7.3 mm/yr (the short-term InSAR measurements supported by GPS measurements generated by Higgins et al. (2014) are significantly higher than the point measurements, as InSAR records overall downward motion, not direct ground sedimentation or tectonics as one would find in sediment cores (Higgins et al., 2014, Higgins pers. comm.)). With a high standard deviation relative to the mean value, the mean is not a good representation of the full spread of data. To better understand this, results have been analysed per geological era and land use. Table 3 indicates results by geological era, with recent measurements (less than 1000 years) highlighted as a period where man has had a more significant and persistent impact on the delta than in previous millenia. Subsidence reported in this recent time, has a higher rate (8.8 mm/yr) than measurements over much longer time periods (as little as 1.2 mm/yr). However, the standard deviation of the results increases in more recent time, compared with long-term records, indicating a greater variability and spread in results. These outcomes cannot be interpreted as indicating that subsidence has increased throughout time; merely that rates are higher, as presently the cause of these rates are unknown. One plausible explanation is the measurement method. For example, GPS stations may be positioned in a place of known subsidence. Alternatively, as subsidence is a long-term process, only a partial record of subsidence may be recorded.

Table 4 summaries the statistics for the point measurements by land use, dividing artificial areas into the three largest cities. Due to the multiple causes of subsidence over different timescales and often localised measurements, it is difficult to generalise a rate of subsidence for each land use type. The maximum rate is recorded in Kolkata, and the lowest in the Barind Tract, in north-west Bangladesh. Measurements in the eastern half of the basin where irrigated croplands are dominant, have the second-to-highest mean rate of subsidence and wide range of measurements. The mean rate of subsidence of irrigated cropland is twice that of rainfed croplands. Land cover may not be the cause of this, and other factors such as underlying geology and the use of groundwater for irrigation are probably more important. This warrants further research. Along the coast, results indicate an increase in subsidence from west to east (contrary to earlier reports and GPS measurements reported in Schiermeier, 2014), but this may partly reflect fewer measurements in the eastern part of the delta (with the exception of recent InSAR data by Higgins et al., 2014). The Sundarbans have the lowest rate of subsidence with a mean value of 2.8 mm/yr, and a median value of 2.0 mm/yr (see Supplementary Material). In Kolkata and Dhaka, subsidence is notably higher suggesting that anthropogenic influence is affecting the rate. The standard deviation in Kolkata is also high with respect to its mean value, indicating a wide variation in rates, but this may reflect the measurements methods and short duration of measurements employed (see Table 1 and Section 3.4). Subsidence in Khulna is less than the other large urban centres, with a mean of 3.5 mm/yr, and a relatively smaller standard deviation. Khulna is a much smaller city than Dhaka and Kolkata so one can argue the human pressure is lower. Thus, in the delta region, whilst there may be local, sometimes short lived variations, often due to a specific cause

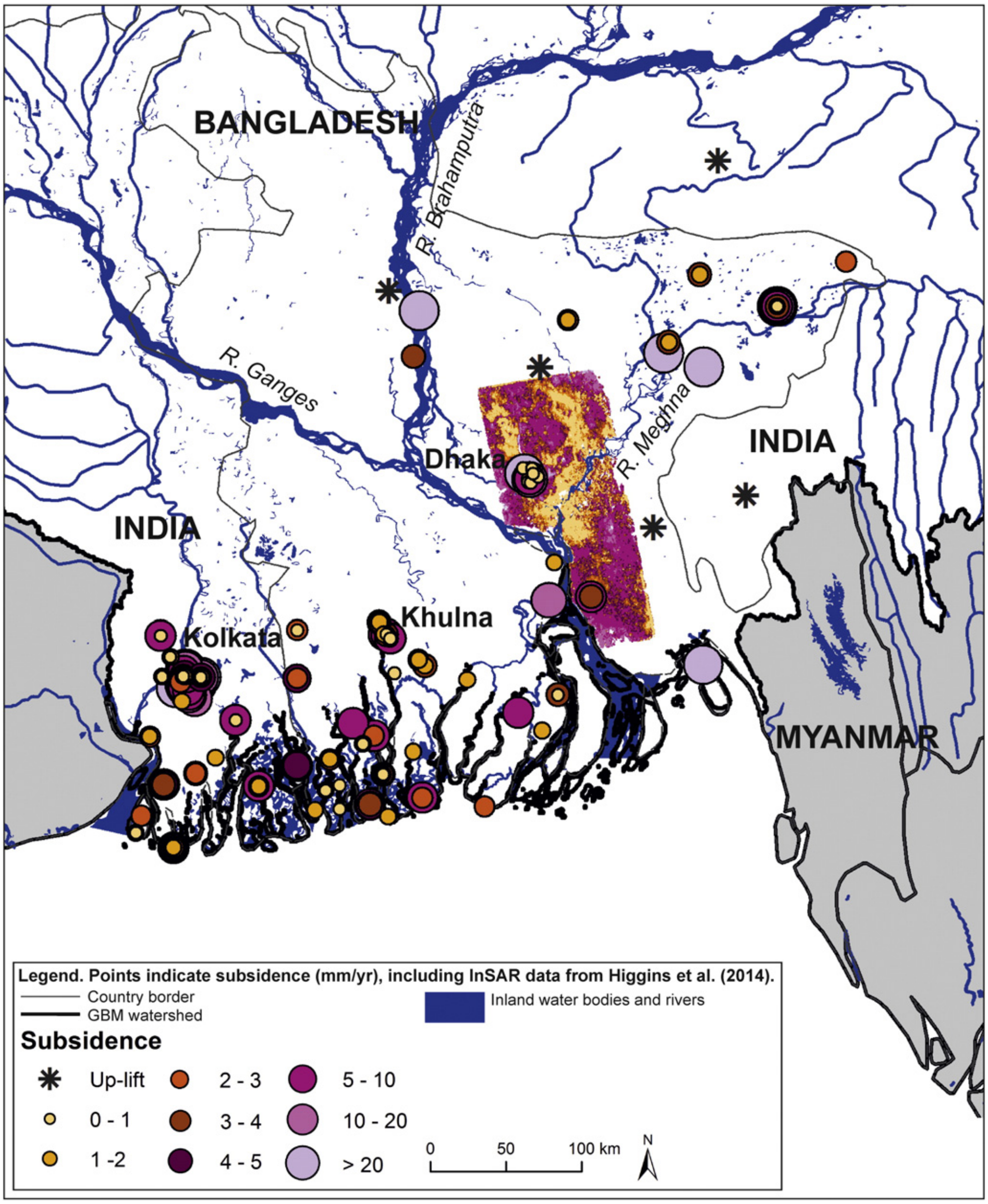

Fig. 5. Rates of subsidence recorded from the literature for the GBM delta and parts of the interior of the basin (see Tables 3, 4 and Supplementary Material and kmz file for rates. InSAR regional data provided by Higgins et al., 2014).

(or due to the method employed), median long-term subsidence is reported at 2.9 mm/yr. Short-term rates further inland are up to 18 mm/yr, and up to 10 mm/yr in Dhaka (Higgins et al., 2014).

Many measurements do not attribute subsidence to a certain depth beneath the surface, so it is difficult to pin-point a cause. This could be subject to a new detailed study. However, Higgins et al. (2014) does attribute subsidence rates to causes, most specifically geology. They note the lowest rates appear primarily in Pleistocene (2.6 Ma to 11,700 years BP) Madhupur Clay, whilst the highest rates occur in Holocene organic-rich muds. However, InSAR measurements do not take account of recent sedimentation. Therefore, taking account of all measurements, it is difficult to determine which rates are exacerbated by man or which have a natural cause. Subsequently projecting future rates is challenging.

3.4. Subsidence age and methods

Fig. 6 analyses the rates of subsidence against measurement method. In the figure, data is divided into land use type, then sorted by method, longitude (from west to east) and rate (high to low). It is recognised that land use type is not the only control on the rate of subsidence, so the figure must be interpreted with caution. In rainfed croplands in the east and north of the study area, the methods which report the highest rate of subsidence are groundwater levels, and secondly, borings/well/auger. Further west again in shrubland, there are only two rates of subsidence where measurement methods exist, making conclusions difficult. In the Sundarbans, subsidence rates are some of the lowest in the delta area, with many measurements being made over the Holocene by carbon dating, tank excavations or borings/well/auger methods, which could reflect long-term geological processes. In the east of the delta, irrigated croplands have the highest standard deviation of rates of subsidence compared with other land use types. Geomorphic surveys also report high rates, but these may be erroneous. In urban areas, longitude is less important as rates are measurement in relative close proximity. Measurement methods are extremely important in Kolkata, where particularly high rates are reported for measurement by groundwater levels. This may be because of the measurement calculations themselves, as well as the short duration of measurements. By omitting this measurement type, a mean value of 3.1 mm/yr and median of 2.4 mm/yr are recorded (instead of 8.6 mm/yr and 7.1 mm/yr, respectively): this may be more representative of long-term subsidence. In Khulna, the measurements are dominated by carbon dating. This also occurs in Dhaka, but other measurement methods, typically those with a shorter period of measurement indicate a high rate of subsidence.

Fig. 7 indicates the period over which the subsidence rates are measured. From the measurements where the age of subsidence is known, 93% are of Holocene age. Whilst some older Holocene measurements exhibit very higher rates (greater than 20 mm/yr), it is generally those in the last five hundred years – when man has had a great influence in the area – that indicates these higher values (i.e. greater than 5 mm/yr). These were measured by GPS, groundwater levels, and archaeological measurements. Thus, it may be that GPS and archaeological measurements have been taken in areas known to demonstrate high rates of subsidence or can easily be visually seen and measured.

4. Discussion

4.1. Land and sea-level changes

This synthesis of subsidence measurements show an overall mean value of 5.6 mm/yr, a median value of 2.9 mm/yr, and a standard deviation of 7.3 mm/yr across the entire dataset. So far in this paper the analysis has made no additional assumptions about the data reported in the literature. Using the full dataset in the Supplementary Material, measurements known to be wrongly cited, vague or where additional assumptions were made (however good or bad these assumptions may be) were excluded from the dataset. This reduced the mean rate of subsidence to 3.9 mm/yr, a standard deviation of 3.4 mm/yr and a median value of 2.9 mm/yr. These measurements are a better reflection of broad and varying conditions in the delta system, but further research is required to carry out a more in-depth assessment.

Subsidence data is affected by age of measurement. Through the Quaternary (from 2.6 Ma BP), sediment would have by-passed the GBM basin, and have been deposited in the deep sea fan during low stands of sea level, and trapped in the delta in high stands of sea level. Hence, at the start of the Holocene, most of the sediment load was trapped within the delta, with large pulses of sediment input (Coleman, 1969; Goodbred and Kuehl, 2000b; Goodbred et al., 2003). At shorter timescales, other variations are apparent. The 18th/19th century shift in the course of the Brahmaputra river due to an earthquake (tectonics and an upward displacement of the land) greatly reduced sediment delivery in the Sylhet Basin, leading to basin deepening (Coleman, 1969; Goodbred et al., 2003; Morgan and McIntire, 1959), lowering relative land levels. Such natural changes represent a minimum rate of subsidence. Reported rates of subsidence are higher over the last few hundred years. This may be due to partial records, measurement method, but increasing human influence (e.g. polders or barrages restricting sediment movement, restricting sediment dispersion on the land) is likely to have a role. Further research is certainly required to produce better data and relate this to the causes of subsidence.

Evidence for recent changes may also be seen in relative sea-level trends (i.e. land and sea-level changes). Using data extracted from Holgate et al. (2013) and the Permanent Service for Mean Sea Level (2014), Fig. 8 illustrates that relative sea-level rise varied from 4 mm/yr (Hiron Point) to 19 mm/yr (Khepupara). Church et al. (2013) report global mean sea-level trends as 1.7 ± 0.2 mm/yr (1901–2010). However in situ measurements and shorter-term satellite studies in the Indian Ocean indicate sea-level rise is greater than the global mean (Han et al., 2010; Unnikrishnan and Shankar, 2007). Using the two longer (50 + years) records of Diamond Harbour and Kolkata, (greater confidence is given to 50 + year records, following Douglas, 1991), these observations suggest net subsidence rates are a maximum of approximately 3 mm/yr. For Diamond Harbour, this is similar to ambient point measurements, whilst in Kolkata, the rate is approximately half that of the measured subsidence values. However, this may be because the main methodology employed to estimate subsidence in Kolkata (i.e. groundwater levels) reports higher values, thus over estimates net subsidence. Omitting the methods that use groundwater levels gives a mean value of 3.1 mm/yr (see Section 3.4), which is close to the rates implied by tide gauge records. Furthermore, the building of the Farakka Barrage (completed in 1975) and other engineering works (Fig. 4) may have altered the rate of relative sea-level change (Brammer, 2014) due to interaction of fresh and saline water, affecting seasonal water levels, plus sedimentation patterns which affect net subsidence. Pethick and Orford (2013) found that in three tide gauges, effective sea-level rise (which represents changes in high water levels and an increase in tidal amplitude), were typically an order of magnitude greater than that of mean sea-level change as water levels were constrained and natural flooding and sedimentation reduced, thus aggravating subsidence and sediment compaction. Thus, man's direct influence on the land can have a greater effect than natural change.

4.2. Implications

Subsidence contributes to relative sea-level rise, and reinforces the impacts of eustatic sea-level rise, thus affecting environmental quality, livelihoods and well-being. Localised subsidence can induce local problems such as building collapse, foundation failure and unpredicted damage, as well as localised flooding. In urban areas, subsidence appears to be greater than in rural conditions possibly reflecting greater sediment compaction and/or groundwater withdrawal and drainage (Table 4). Urban population is projected to increase from 2010 to 2025 by 29%, 49% and 43% in Kolkata, Khulna and Dhaka, respectively (cf., UN-Habitat, 2013) so human pressure and potentially subsidence is likely to increase. In rural environments, subsidence could bring greater flooding and salinisation, which is already a major problem in the delta. Polders preclude sedimentation and exacerbate the loss of land elevation (Auerbach et al., 2015). More dynamic management, including controlled floodwater management and sedimentation has been suggested as a response to this challenge (e.g. Brammer, 2014). Alternatively, changes in land use can be considered (e.g. conversion to aquaculture), although this can result in other environmental problems affecting rural livelihoods (e.g. see Paul and Vogl, 2011). Subsidence can also lead to increasing saline conditions and soils affecting farming and Sundarbans mangrove forest, although it is acknowledged that many other factors play important roles. Paleo evidence indicates that mangroves have been able to cope with relative sea-level rise, so it is likely they will do so in the future (Woodroffe, 1990), but may struggle under conditions of rapid rise. Under such conditions of rapid sea-level rise species in the forest may shift to more salt-tolerant plants, as already seen in the subsiding western delta (Blasco et al., 1996).

Development is subject to multiple stresses, including land/sea-level change, of which subsidence plays an important role in deltas. As this paper has shown, subsidence in the GBM delta can be a greater threat than eustatic sea-level rise today, and this may remain true into the future even as climate-induced sea-level rise accelerates. Brammer (2014) recognises that communities residing in the GBM delta are adaptable to change, but the combined pressures of land/sea-level change, salinisation and rapid urban population growth provide multiple challenges. This paper supports Brammer (2014) that an integrated approach to development is required: Part of this requires further monitoring to understand multiple drivers of change in a complex geomorphic setting, including subsidence, and how this influences wider development and human livelihoods. Ideally ongoing monitoring of subsidence is required over large scale areas, such as though InSAR, augmented with accurate ground truth data based on a solid methodology where there is high confidence in the result.

Table 2
A summary of sources that reports subsidence rates, by measurement type, geological era and measurement method. Note that only the key reference is provided, and additional assumptions regarding the core data may have been made, or other sources cited. Multiple key references may cite a single data source. For further information, see Supplementary Material.

	Measurement type	Geological era					Measurement method		
Key reference	Based on point or area rates?	Pliocene	Pleistocene	Holocene	Recent	No information, not defined or clear	Archaeological	Borings/well/auger	Carbon dating
Alam (1996)	Point			X		X		X	X
Allison et al. (2003)	Point					X			
Bhattacharya et al. (2004)	Point				X				
Brammer (2014)	Point			X	X				X
Chatterjee et al. (2006)	Point				X				
Chatterjee et al. (2007)	Point				X				
Ericson et al. (2006)	Area				X				
Ganguli (2011)	Point				X				
Goodbred and Kuehl (2000a)	Point			X					X
Hanebuth et al. (2013)	Point				X				X
Hazra et al. (2001)	Point					X			
Higgins et al. (2014)	Point/area				X				
Hoque and Alam (1997)	Point		X	X		X		X	X
Hübscher and Spieß (2005)	Area		X	X	X				
Islam et al. (1999)	Point		X						X
Johnson and Alam (1991)	Point	X	X						
Khan and Islam (2008)	Point/area					X			
Morgan and McIntire (1959)	Point					X			
Ostanciaux et al. (2012)	Area				X				
Pethick and Orford (2013)	Point					X			X
Sahu and Sikdar (2011)	Point				X				
Sarker et al. (2012)	Point				X		X		
Schiermeier (2014)	Area				X		X		X
Stanley and Hait (2000)	Point		X	X	X				X
Steckler et al. 2008b	Point				X				
Steckler et al. (2010)	Point				X				
Warrick et al. (1996)	Point			X	X	X			
Worm et al. (1998)	Point	X							

5. Conclusions

Subsidence is the norm in deltas, yet is poorly understood in many cases. In the Ganges–Brahmaputra–Meghna delta, good quality data for the whole region is sparse, with recent InSAR measurements published only over one large region. Natural and anthropogenic causes, and their interactions are not well understood. Importantly past analyses of subsidence often cite a limited sub-set of the reported subsidence rates, without fully exploring the entire record or justifying their selection. From a thorough literature search, 205 subsidence rates (duration 5 million years to 3 years) from 24 author teams citing 22 articles were found. Taking all measurements regardless of locality or temporal constraints, the overall mean rate was 5.6 mm/yr and the median 2.9 mm/yr, with a standard deviation of 7.3 mm/yr. Excluding unclear or unreliable results, or where additional assumptions were made, this reduced to an overall mean rate of subsidence to 3.9 mm/yr, a median rate of 2.9 mm/yr, with a standard deviation of 3.4 mm/yr. Further analysis into the reliability and quality of data, relating to the causes of change would be beneficial.

Table 3
Summary of results, showing the minimum, maximum, mean, median, and standard deviation (to 1 dp) of the rate of uplift or subsidence for each geological era based on point data where age is known based on the entire dataset. 'All records' also includes those where the date is not defined or clear. Recent is defined as less than 1000 years, when man has had significant influence in the delta. See Supplementary Material for full information.

Geological era	n	Min	Max	Mean	Median	Standard deviation
Recent (<1000 years)	65	−0.4	43.8	8.8	7.4	7.5
Holocene (excluding recent)	84	0.2	24.4	3.5	2.0	4.8
Pleistocene	8	0.5	4.0	1.8	1.2	1.4
Pliocene	2	1.2	1.2	1.2	1.2	0.0
All records	205	−1.1	43.8	5.6	2.9	7.3

Higher mean rates are found in the northern delta, which is associated with irrigated croplands, and the cities of Kolkata (the latter partly due to measurement method) and Dhaka. The most recent measurements, where many are measured over short time periods, also show a higher rate of subsidence compared with longer-term rates. This could reflect the different methodologies employed and/or human enhancement of subsidence. Subsidence, particularly when influenced by man can be highly localised. Further research is required to document the causes of these high rates. Contrary to previous research, the highest subsidence rates were recorded in the eastern part of the delta, rather than the west (excluding measurements from Kolkata). This may be due to sampling bias as many more measurements were found in the western portion.

Due to the multiple and ongoing causes, subsidence will continue and needs to be considered in development of the delta. The combined effects of land and sea-level change should be considered, including factors outside the delta that influence net subsidence (e.g. reservoir building changing stream flow and reduced sediment availability) (cf., Syvitski et al., 2009). In rural coastal areas, highly dependent on agriculture and at threat from sea-level rise, small differences between projected and actual annual subsidence measurements can make a difference between one course of action and another. In urban areas, subsidence remains a long-term challenge which is difficult to manage, especially given the rapid rate of urbanisation which is often unplanned. Development agencies are increasingly focused on climate change and its effect on well-being as an issue: in deltas, subsidence also needs to be similarly treated (cf., World Bank, 2010).

Monitoring of subsidence needs to be continued and improved to better understand it. Whilst longer-term surveying over a wider geographical area, such as by InSAR satellite data and GPS measurements

Geomorphic survey	GPS	Gravity survey	Groundwater levels	InSAR measurements	Magnetostratigraphic dating	Neotectonics	Tank excavation	Other	No information, not defined or clear
									X
									X
			X						
				X					
				X					
								X	
			X						
						X			
								X	
									X
	X			X					
X		X				X	X		X
								X	
						X			
									X
X									
								X	
	X							X	
			X						
	X								
	X							X	
	X								
	X								
									X
					X	X			

are emerging, it is challenging to determine long-term trends as these measurements are undertaken on relatively short time-scales. Long-term, sustained investment in monitoring is required, to capture both short and long-term change. Given the nature of this research, the authors are aware that further studies of subsidence in the GBM delta probably do exist but are presently inaccessible. This data, any newly published data (e.g. Reitz et al., 2015), plus the results presented in this paper, could form part of an additional study to determine the more detailed reasons as to why subsidence has occurred and what factors could control future rates. Lastly, these methods could be applied to other deltas where subsidence is important, but systematic studies are unavailable.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.scitotenv.2015.04.124. These data include a spreadsheet and Google map of the rates of subsidence described in this article.

Table 4

Summary of results, showing the minimum, maximum, mean, median, and standard deviation (to 1 dp) of the rate of uplift or subsidence for each land use type based on point data. The entire dataset is used. Urban areas are divided into the three largest cities. Note that the type of land cover may not be responsible for the cause of subsidence, as many other factors need to be considered. See Supplementary Material for full information.

Dominant land use (extracted from GlobCover, 2009)	n	Min	Max	Mean	Median	Standard deviation
Closed to open shrubland, broadleaved evergreen, mosaic vegetation (outside of maximum Holocene transgression shoreline)	3	−0.4	−0.1	−0.2	−0.3	0.1
Irrigated croplands	36	−1.1	41.0	8.5	3.7	10.6
Rainfed croplands, mosaic vegetation, mosaic croplands	62	−0.6	31.7	4.3	2.3	6.5
Sundarbans	36	0.7	7.1	2.8	2.0	2.0
Urban — Kolkata	40	0.5	43.8	8.6	7.1	7.8
Urban — Khulna	15	1.0	10.0	3.5	2.9	2.4
Urban — Dhaka	13	0.4	22.0	5.9	1.0	7.3
All records	205	−1.1	43.8	5.6	2.9	7.3

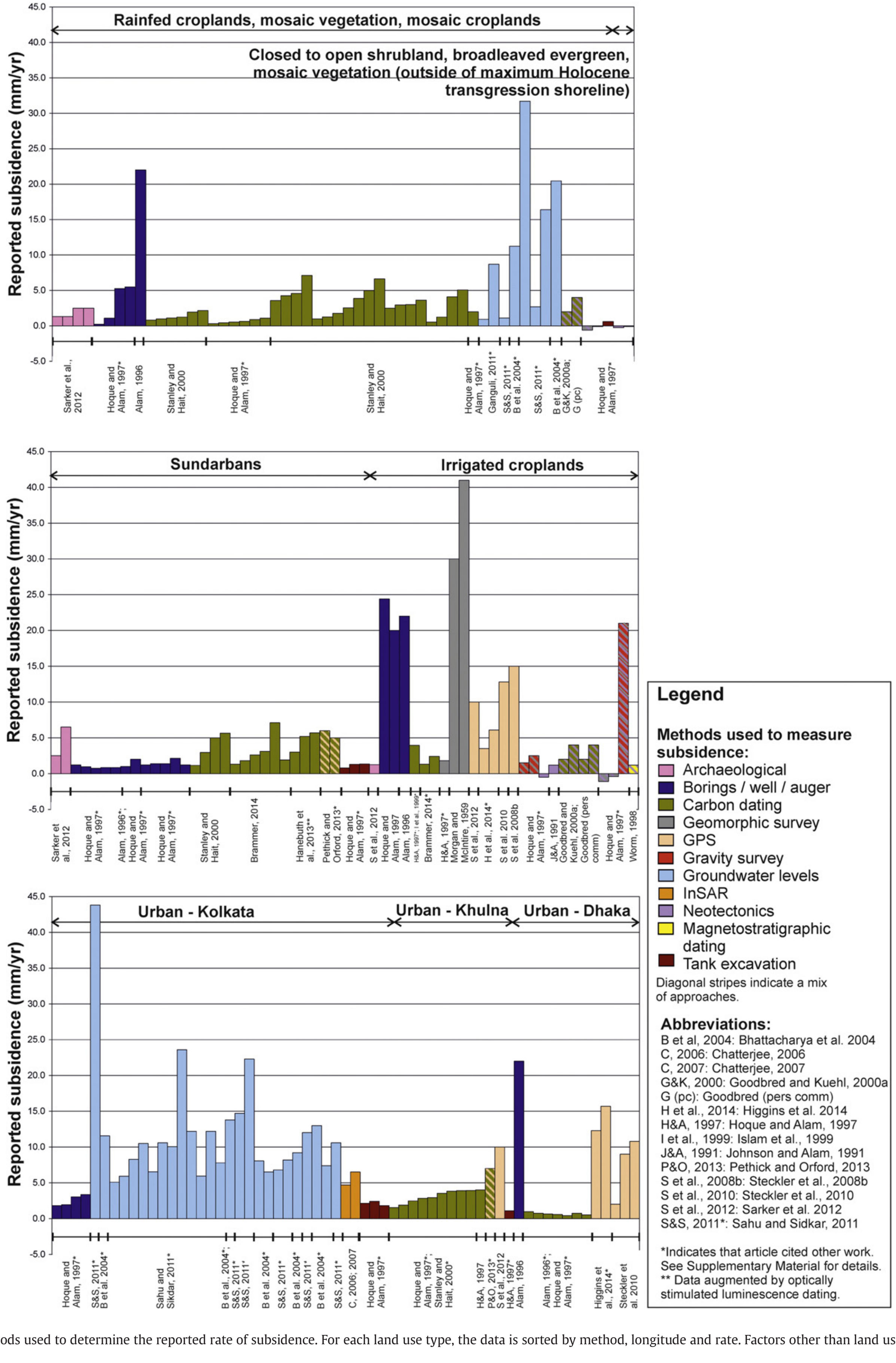

Fig. 6. Methods used to determine the reported rate of subsidence. For each land use type, the data is sorted by method, longitude and rate. Factors other than land use type affect subsidence.

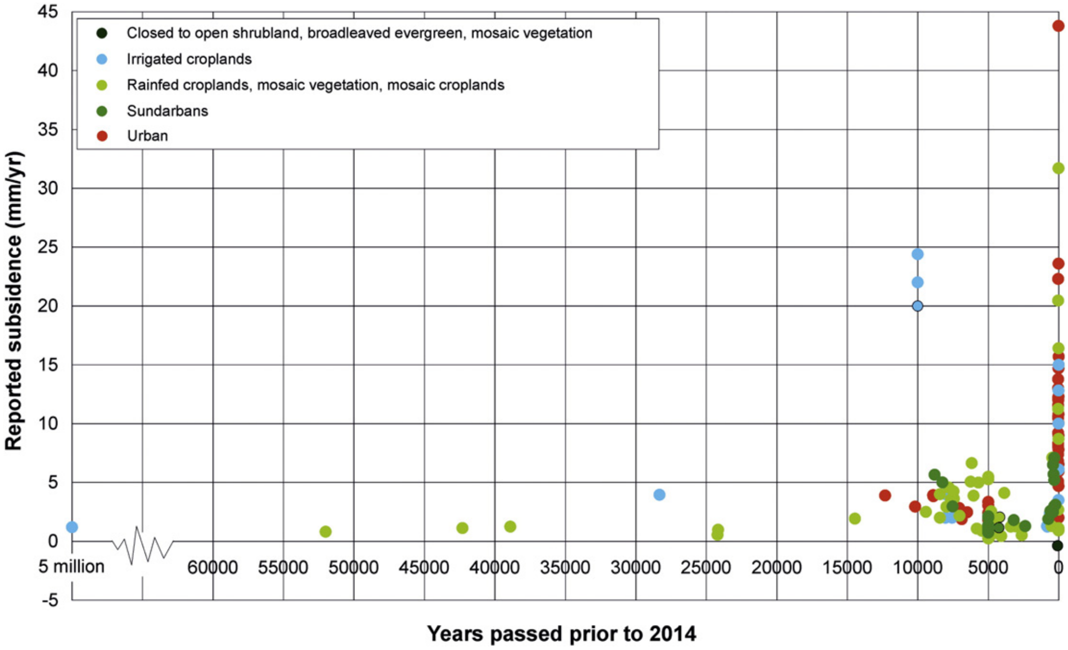

Fig. 7. Reported rate of subsidence according to land use type against age. Please note that factors other than land use type affect the rate of subsidence. Where a range of measurement time was reported, the mid value was taken.

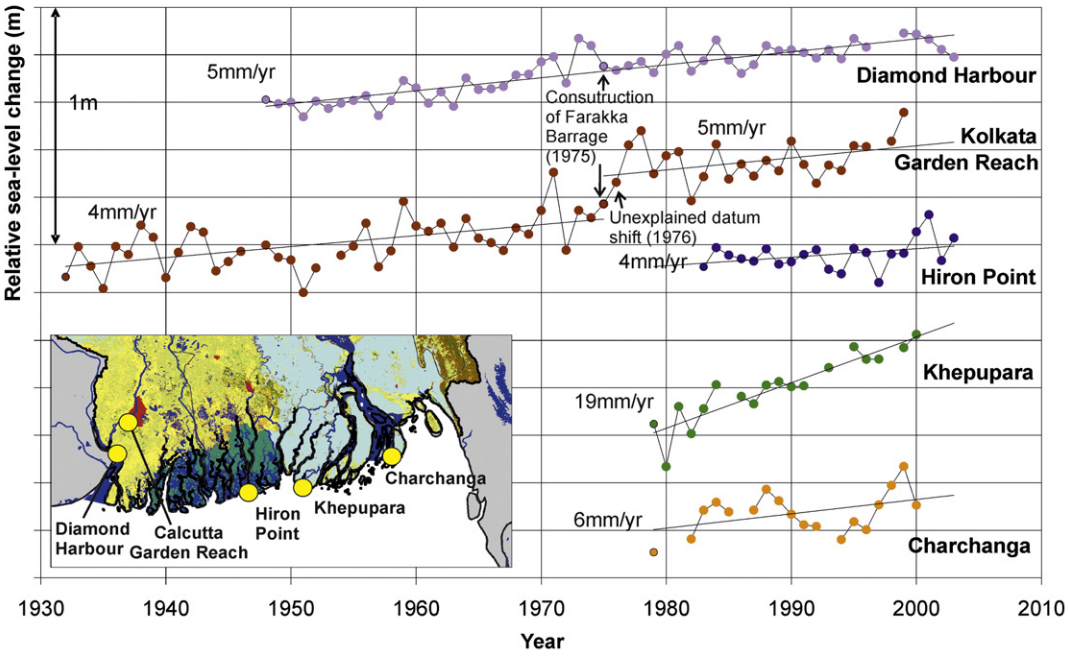

Fig. 8. Relative sea-level rise obtained via tide gauge records from Holgate et al. (2013) and Permanent Service for Mean Sea Level (2014). Records are offset for display purposes.

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