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

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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

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

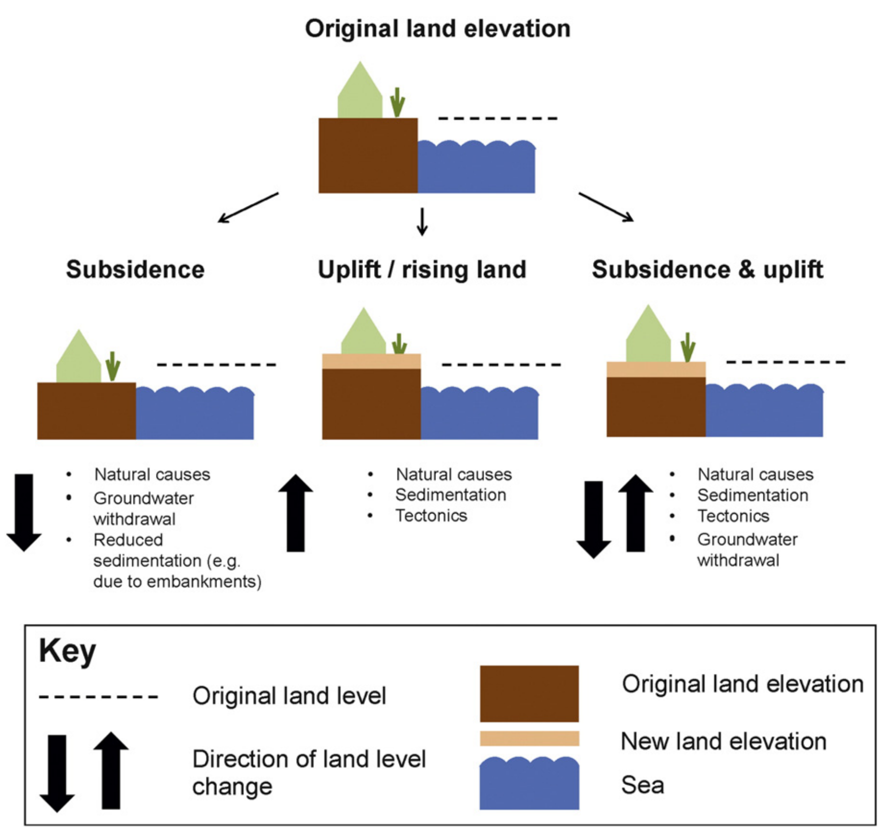

Fig. 1. Potential examples of how land elevation changes over time due to land uplift and subsidence.