Relative Sea Level Changes and Worsening Floods in the Western Pampanga Delta: Causes and Some Possible Mitigation Measures

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ABSTRACT

Despite declining rainfall, flooding continues to worsen around the northern end of Manila Bay. In Pampanga, flooding is enhanced by siltation of streams by sediments from the 1991 Mt. Pinatubo eruption, but the entire region has always been flood-prone, and Bulacan and Metro Manila, far from Pinatubo, also suffer worsening floods. Urbanization and deforestation are blamed, but have less impact than local sea level rise. Global warming causes the ocean surface to rise only 2 mm/yr; localized subsidence of the region from both natural and anthropogenic causes is an order of magnitude faster. Movements associated with faulting and the Pinatubo and Taal volcanoes probably are less important than the compaction of deltaic sediments under their own accumulating weights. All natural causes of subsidence are dwarfed by the contribution from excessive groundwater withdrawal, which greatly facilitates natural sediment dewatering and compaction. Several centimeters per year of documented subsidence at well sites have been corroborated by recent resurveys of elevation benchmarks established in the 1950s.

In the short-term, flooding can be ameliorated by restoring original channel widths and by modifying current aquaculture practices. In the longer term, reforestation should also help by increasing infiltration and decreasing erosion and siltation. Flooding will inexorably continue in the coming century, however, both from natural compaction of delta sediments and from global sea level rise. Subsidence will continue to accelerate if the use of groundwater by the growing population is not regulated and reduced.

INTRODUCTION

The Pampanga Delta is largely situated in the province after which it is named; however, its western and eastern fringes, respectively, lie in the adjacent provinces of Bataan and Bulacan and extend southward into the northern Manila suburban area called KAMANAVA, which is composed of the municipalities of Kaloocan, Malabon, Navotas, and Valenzuela (Fig. 1). The delta is heavily populated and fertile, with valuable, highly developed agri- and aquaculture.

Worsening floods in this region have been drawing much attention over the past decade. Widely-cited causes include the various effects of unchecked urbanization: decreased infiltration and increased runoff of rain waters due to the increase in paved areas; encroachment of

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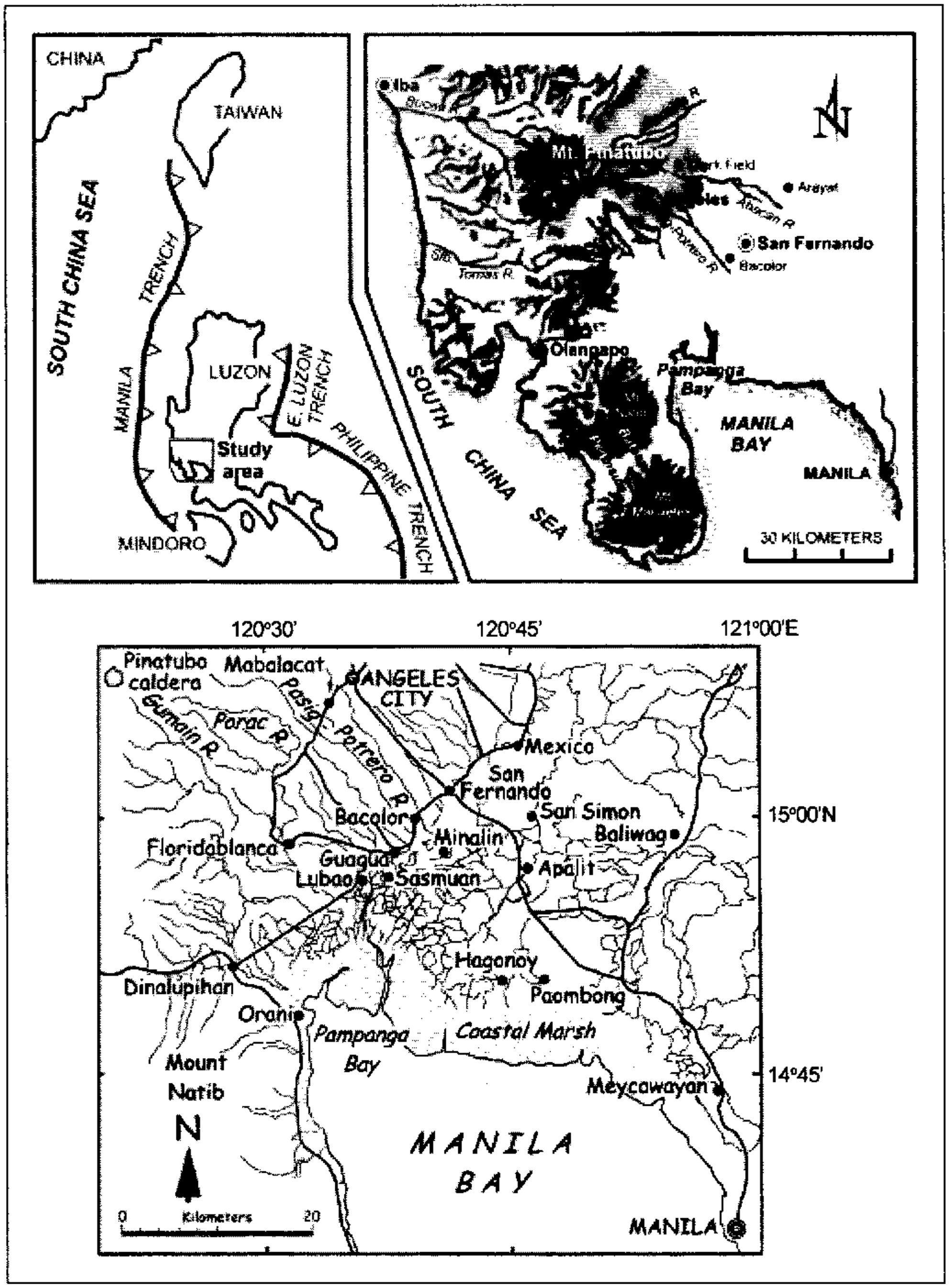

Fig. 1. The study area. (Top left) Location. The presence of two subduction zones may contribute a minor "slab drag" component of subsidence. (Top right) Manila Bay and Mt. Pinatubo. (Bottom) Details of study area. Note the abundance of streams that contribute sediment to the delta complex.

channels by squatters and fishponds; and choking of streams by improper garbage disposal. Increased runoff and slope erosion as a consequence of deforestation are also generally recognized causes. Additionally, since the 1991 Mt. Pinatubo eruption the western Pampanga Delta has been experiencing enhanced flooding, which commonly is being attributed to channel filling by eruption debris. True, in the monsoon-typhoon seasons of 1991 and succeeding years, great amounts of the eruption debris have been mobilized into catastrophic lahars. Stream channels in Pampanga Province, both within the range of lahars and farther downstream, have been filled with the reworked volcanic sediments. It is important to note, however, that the area was already notorious for flooding long prior to 1991. Furthermore, coastal Bataan and Bulacan provinces and the KAMANAVA area, although essentially unaffected by large-volume volcanic sedimentation, are also experiencing aggravated flooding. This indicates that contributory factors independent of Pinatubo-related sedimentation probably are more important in the long term.

Only recently has the phenomenon of global sea level rise entered the public consciousness, which, however, still has to accept that deltas subside naturally at much faster rates than eustatic sea level rise. That this natural subsidence may be greatly aggravated by excessive withdrawal of groundwater has been recognized by the general public and decision makers in other countries, but not in the Philippines.

Our work in the region to examine the role of the different factors that contribute to subsidence began in the western portion of the delta in 1998, funded by the Center for Integrative and Developmental Studies of the University of the Philippines (Siringan & Rodolfo, 2001). Our continuing research, funded since 2001 by the Department of Agriculture's Bureau of Agricultural Research, with supplementary support from Oxfam Great Britain–Philippines, is now analyzing the entire delta. We employ a variety of approaches including precise elevation measurement with global positioning systems (GPS); time series analyses of satellite images; sediment coring; field inventories of water wells and analyses of the data they yield regarding rates of subsidence; and systematic social surveys of the inhabitants to elicit their knowledge and experiences of flooding in the past.

Some of our approaches will yield results in the future. For example, our GPS stations will be reoccupied in one or two years, and our sediment cores are still being analyzed and have yet to be subjected to age dating. Our early results, however, clearly indicate that the aggravated flooding is largely due to local, relative changes in sea level. Most prominent among the possible causes is subsidence due to over-pumpage of groundwater. The subsidence-induced sea level changes are not receiving sufficient attention in planned and proposed mitigation measures, which include multi-billion dollar dredging projects in the delta that could well be futile. Given the serious economic and social factors, we present this progress report, utilizing mainly the data we initially gathered in the western delta. We examine several factors that could contribute to enhanced flooding, present our initial evaluations of them, propose avenues for continuing research, and suggest a few measures that could mitigate the problem.

Geologic and geographic setting

The Pampanga Delta and contiguous flood-prone lowlands occupy about 2,700 km^2 of the southern central valley of Luzon Island, from Angeles City and Arayat town in the north to the coast stretching eastward and southward from Pampanga Bay to the northern outskirts of Manila (Fig. 1). To the west, the area is bounded by Pliocene to Recent volcanic rocks of the eastern Zambales Mountains, including Mt. Pinatubo and the Bataan peninsula, which comprises Mts. Natib and Mariveles, two dormant volcanoes that are the southern sisters of Mt. Pinatubo; to the east, the plains about the Sierra Madre mountain range, a complex of Eocene ophiolites and Neogene marine and terrestrial sedimentary rocks (Encarnacion et al., 1993; Bureau of Mines and Geosciences, 1981). Seismic-reflection data and exploratory boreholes show a column of Miocene to Recent deltaic and shallow-marine rocks more than 7 km thick beneath the onshore and nearshore (Bureau of Energy Development, 1986). In Fig. 2, a Landsat image taken in 2001, the distinct, sharply linear northwestern limit of the delta plain is one of several lineations clearly apparent in satellite imagery. These features may be the surface expressions of active faults.

Situated mainly in Pampanga province, the deltaic complex extends southwestward and eastward into the adjacent provinces of Bataan and Bulacan, respectively. Its southeastern limit includes Metro Manila's KAMANAVA area. Besides being heavily populated, the delta is a major source of food, being highly developed as both a "rice and sugar basket" and a "fish basket". Seasonal monsoonal flooding, with its adverse economic and hazardous effects, is aggravated by local sea level rise, both short-term as a consequence of wave and storm setup during the southwest monsoons and typhoons, and the longer-term changes due to eustasy and subsidence. The delta plains are extremely vulnerable to even minor changes in local sea level, because, along their very gentle surfaces, small rises translate to large, horizontal invasions of the sea. Such saltwater invasions are greatly amplified by the numerous estuaries along which they occur.

The more seaward region, marshy and cut by numerous tidal channels, is utilized for aquaculture ponds which are progressively encroaching northward and occupying larger portions of channels. The grayer areas in Fig. 2 are planted to two annual rice crops. Saltwater intrusion, which already extends more than 20 km inland, is a common reason for the conversion of rice paddies to fishponds.

The area receives about 1,900 mm of rain annually, about 70% during the rainiest months of June through September when southwesterly winds of the South Indian Ocean Monsoon bring maritime equatorial air across the South China Sea (Umbal & Rodolfo, 1996). The most intense precipitation is brought directly by three or four typhoons, or from strong southwesterly airflow drawn in by more distal typhoons, about 17 of which enter Philippine space every year. Typhoons and typhoon-enhanced monsoonal flow is responsible for about half of all the rainfall (Umbal & Rodolfo, 1996).

By an unfortunate combination of coastal configuration and seasonal winds, the same southerly and westerly airflows that deliver heavy rainfall to the region also generates storm "set-up", meaning it temporarily raises sea level at the coast by piling up the seawater against it. Storm set-up can raise high tides by as much as 80% (Siringan & Ringor, 1998), precisely at the time rain-generated floods are seeking outlets to the sea. Manila Bay tides are predominantly diurnal and, like most of the Philippines, microtidal having a tidal range of 1.25 m. The record for highest spring tide, 1.93 m, was set on July 4, 2000 (Nippon Koie, 2001).

Manila Bay receives approximately 1.2×10^{11} m^3 of water from the Pampanga and numerous other rivers (Siringan & Ringor, 1998). Prior to the Pinatubo eruption in 1991, the bayhead plains were already chronically subject to severe monsoonal flooding. The 1991 eruption, the world's most powerful over the last century, left at least 5.5×10^9 m^3 of pyroclastic debris on the volcano flanks (Newhall & Jones, 1996). Since the eruption, flooding has been worsened by great volumes of debris, mobilized into lahars (volcanic debris flows and hyperconcentrated streamflows) and flood sediment. Stream channels in Pampanga province, both within the range of lahars and farther downstream, have been filled with the reworked volcanic sediments. Enhanced flooding commonly has been attributed to this loss of channel

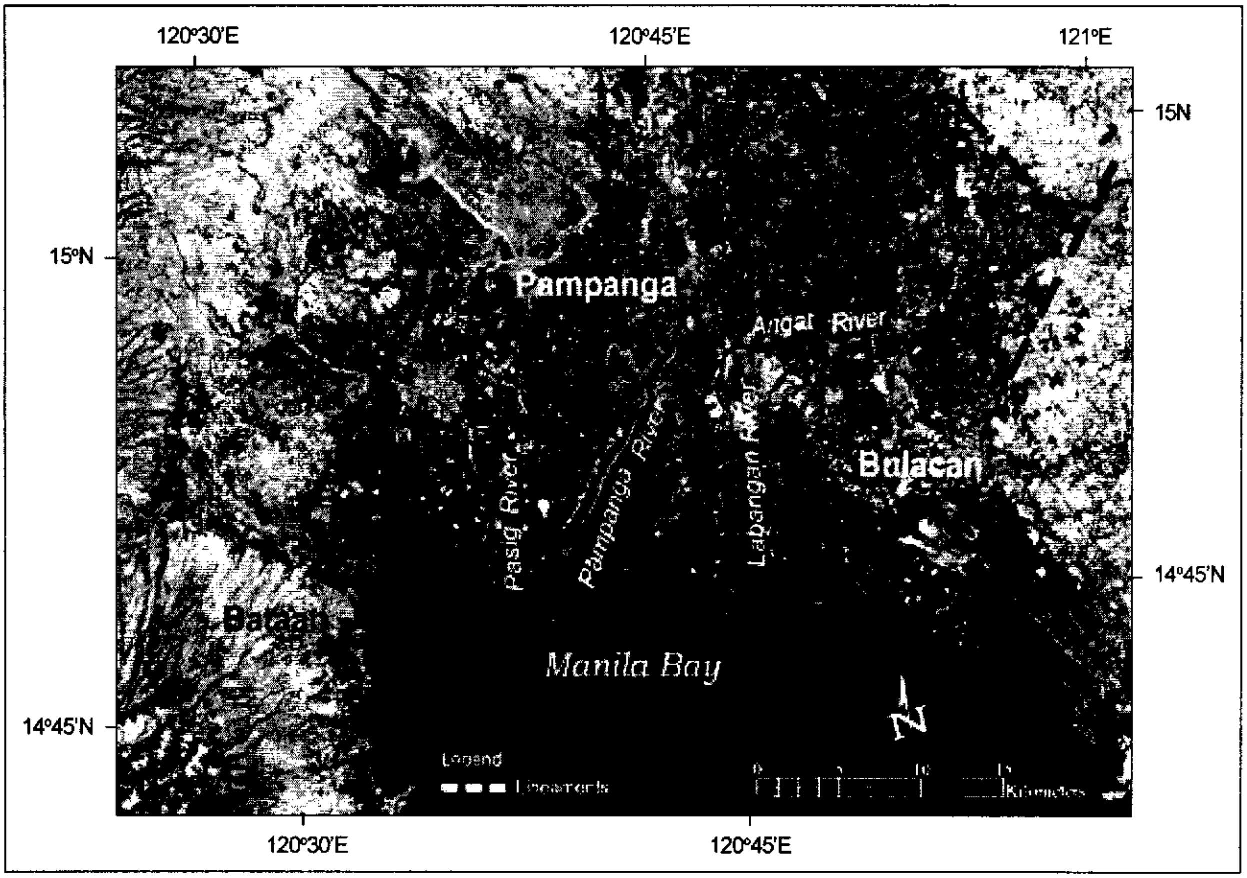

Fig. 2. 2001 Landsat image of the area surrounding northern Manila Bay. Black dash lines represent lineaments.

capacity, but we will show presently that other factors also contribute, and likely are more important in the long run.

Sediment discharged by several major river systems accumulate as a composite delta at the north end of Manila Bay. Before the 1991 eruption, rivers used to discharge about $1.2x10^6$ tonnes of sediment annually into the bay head (Japan International Cooperation Agency, 1982). Santos & Villamater (1986) used ^{137}Cs in sediment from a core 10 km offshore in water, 10 m deep to measure a sedimentation rate of 5.5 cm/yr. The western, offshore portion of the delta has been receiving large quantities of volcaniclastic sediment since the 1991 eruption. Notwithstanding this enhanced delivery of sediment and substantially increased depositional rates, new bathymetric coverage of the nearshore bay floor by Siringan & Ringor (1998) shows essentially no shoaling since 1961. Even prior to the eruption, the greatest sources of sediments were Pinatubo and adjacent portions of the Zambales mountains; and yet, curiously, the shoreline where these sediments are received is physiographically expressed as the Pampanga Bay inlet. Clearly, sedimentation is being offset by local subsidence.

METHODS

Interviews of local and long-time residents, initially informal but now formalized after methodological input from professional sociologists, are some of our main sources of information. Artesian springs and groundwater wells are the main source of fresh water in the region. Both shallow and deep wells are utilized in the area. The shallow wells are only 1 to 2 pipe lengths (~6 to ~12 m long) in depth, whereas the typical depths of the deep wells are 18 to 20 pipe lengths (~110 to ~122 m). Some of the deeper wells appear to rise out of house and well floors as the ground sinks around them. Questions asked include the date the wells were installed and repaired; the total depth of the well; the number of users; the implementing agency and contractor; the quality of water; and record of emergence. Information elicited regarding changes in tide levels include flooding history, with or without associated precipitation, with attention paid to height, duration, and recurrence intervals.

As an independent verification of subsidence rates, thus gathered, we compared them to the rates determined by the Department of Public works and Highways (DPWH). This was done in 2001 by reoccupying three benchmarks established in 1952, three in 1956, and one in 1999 (DPWH, 2001).

RESULTS

Enhanced flooding of the western Pampanga Delta

Informants at 34 sites north of Pampanga Bay reported that typical floods were 1 to 6 ft higher during the 1990s than during the previous decade when typical flood heights were 2 to 4 ft and averaged 3 ft (Fig. 3a; the English system is our informants' unit of choice). Mt. Pinatubo's 1991 eruption is not entirely to blame, however, for the area was already notoriously flood-prone long before 1991, and most of the same informants also reported enhanced flooding of 1 to 4 ft between the 1960s and the 1980s (Fig. 3b). Furthermore, the adjacent Bulacan province, although essentially unaffected by large-volume volcanic sedimentation, is also experiencing aggravated flooding, which indicates contributory factors independent of Pinatubo-related sedimentation that, in the long term, may be more important.

Tidal incursion and infrastructural response

Anecdotal accounts point to worsening incursion of seawater during high tide. Areas that 30 to 40 years ago stood above high tide can now be submerged to depths as great as 1 m, even in the absence of precipitation. Barangays like San Rafael Baruya in Lubao, Pampanga had to raise their roads several times in the last decade. The newest road construction raised it a meter above the floors of adjacent houses (Fig. 4). From this information, we estimate that the subsidence rate is within 3 cm/yr. Many other roads on the delta plain have been raised in response to worsened flooding. We argue that the road raising is a direct consequence of subsidence.

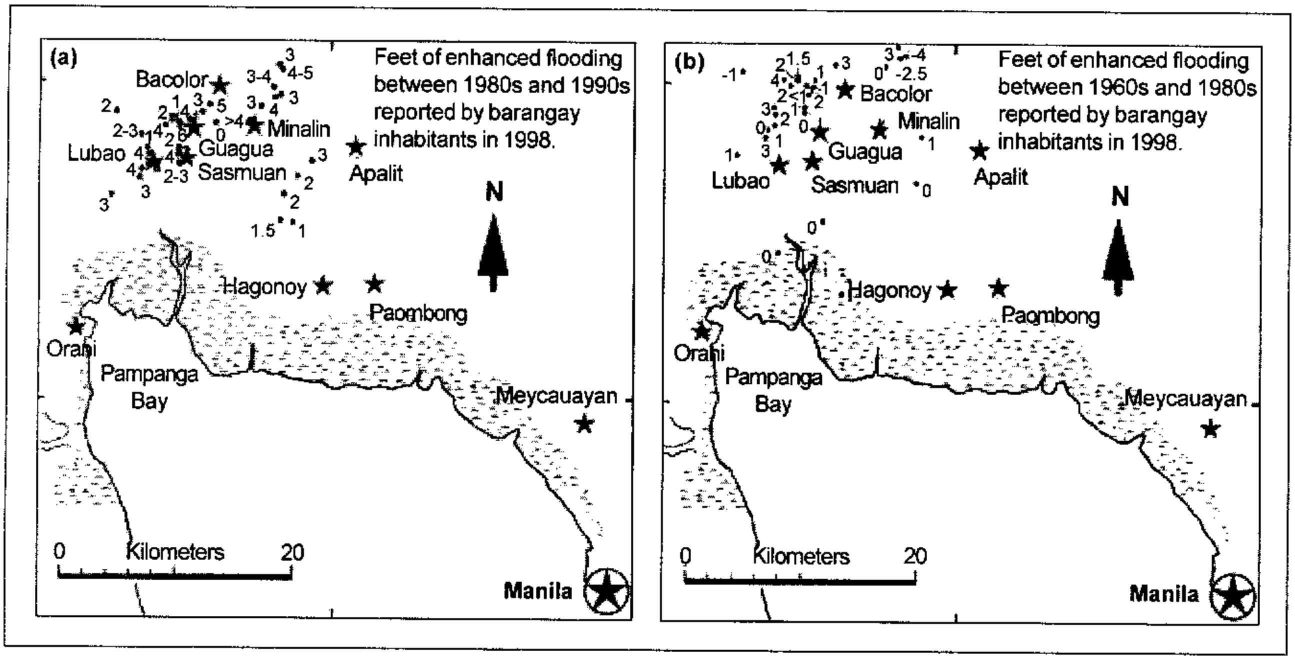

Fig. 3. Enhanced flooding north of Pampanga Bay as reported by local inhabitants (a) between 1980s and 1990s; and (b) between 1960s and 1980s.

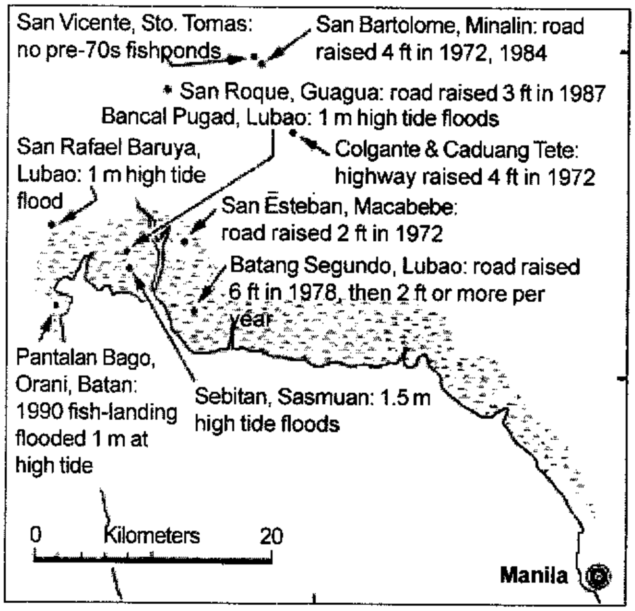

Fig. 4. History of repeated highway raising in western Pampanga in response to enhanced flooding and tidal incursion.

Fig. 5. Patalan Bago fish-landing at Orani, Bataan during an ebbing spring tide.

In Barangay Patalan Bago, Orani, Bataan, a fish landing constructed above high tide levels in 1990 now gets inundated by as much as 30 cm during high tide (Fig. 5). A minimum subsidence rate of 3 cm/yr is indicated.

Emergence of wells and DPWH resurvey data

In the area north of Pampanga Bay, wells only 6 m to 12 m deep did not show subsidence; however, of the

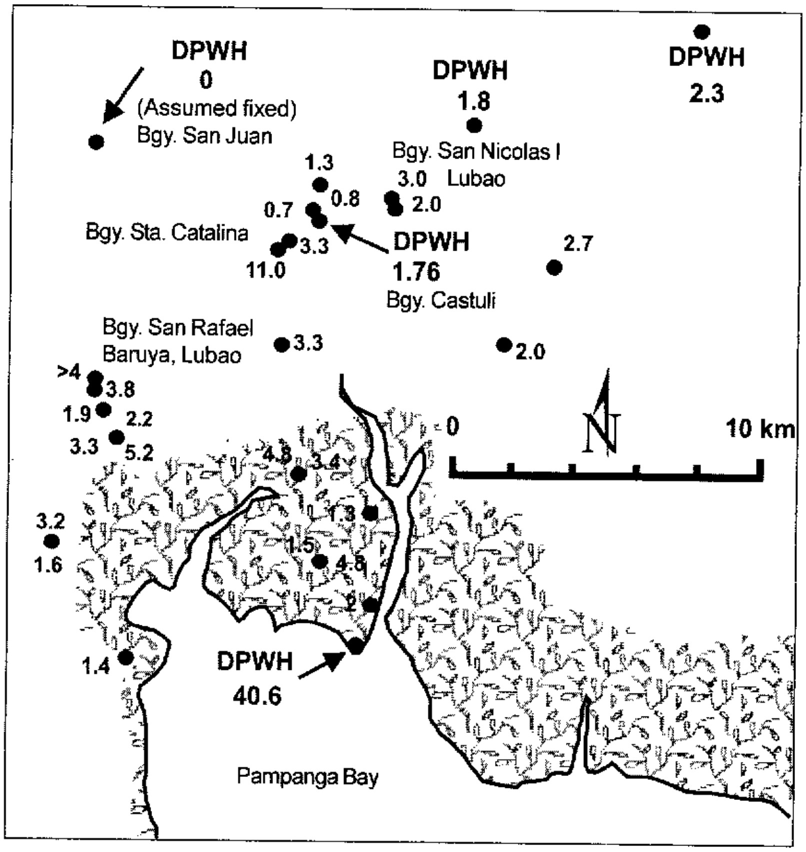

Fig. 6. Wells in western Pampanga Delta that yielded subsidence rates (cm/yr), and subsidence rates determined by reoccupancy of elevation benchmarks by DPWH (2001).

numerous wells that penetrated 110 to 122 m below the surface, only 28 wells yielded data from which we were able to calculate rates of subsidence (Fig. 6). One well yielded a subsidence rate of 11 cm/yr; however, this value is suspect because the typical rates, including those at adjacent wells, were 2 to 4 cm/yr. Ignoring the outlier well, the average for the remaining deep wells is 2.5 cm/yr. The rates derived from the emergence of wells are consistent with the estimates based on accounts that some areas that stood above tide levels 30 years ago are now frequently flooded almost a meter deep during high tide.

The oldest well that yielded subsidence data was established in 1955 in the house of Mr. Antonio Castro in Bgy. San Rafael Baruya, Lubao, Pampanga. Mr. Castro observed the well pipe emerging from the floor of the house almost immediately after it was built. He noticed no change in the rate of emergence following the 1990 Luzon earthquake and, curious to see whether the 1991 Pinatubo eruption would alter the rate of emergence, made a mark on the pipe shortly thereafter. Subsidence rates after the eruption were not substantially different from those before it. Another pump, in the residence of Mr. Mariano Santos, subsided 45 cm from 1978 to 1998. The pre-eruption rate was 2.15 cm/yr, the post-eruption rate was 2.43 cm/yr.

The rates we obtained from emergent wells are entirely consistent with data that the Department of Public Works and Highways (DPWH) obtained in 2001 by re-surveying old benchmarks (DPWH, 2001). Of these old benchmarks, three have been established in 1952, two in 1956, and one in 1999. The rates of subsidence obtained are entirely consistent with those we derived from measurements at wells (Fig. 6).

DISCUSSION

Changing rainfall

The aggravated flooding of the study region cannot be attributed to increased rainfall. A recent statistical analysis of precipitation and seasonal inflows into reservoirs of the region clearly shows that rainfall has actually decreased over the last three decades (Jose et al., 1996), possibly as a consequence of a global shift from La Niña to El Niño dominance starting around 1976 (Wolter & Timlin, 1993, 1998).

The eustatic component of sea level rise

Much worldwide attention is currently being given to the serious socioeconomic effects of future sea level rise due to thermal expansion of surface ocean waters and increased glacial melting, as consequences of accelerating global warming. Estimates of mean global eustatic sea level rise during the last century range from 0.12 to 0.18 cm/yr (Gornitz & Lebedeff, 1987; Douglas, 1991; Turekian, 1996; Mimura, 1998; Pirazzoli, 1998; Mimura & Harasawa, 2000). With continued acceleration of global warming, a sea level rise of as much as 100 cm over the next century has been predicted (Thomas, 1986; Houghton et al., 1990; Warrick et al., 1996); this, however, would be only half of the present rate of sea level rise being experienced by the Pampanga Delta region.

Natural causes of relative sea level rise

Global sea level rise is only a minor factor in many regions of the world, including the Pampanga Delta, compared to relative sea level rise due to local subsidence. At the Pampanga Delta, subsidence is an order of magnitude more rapid than the present eustatic rise, measured in centimeters per year. Theoretically, five natural phenomena may cause this severe local subsidence, and each of the five is potentially a contributory factor at the delta plains of Pampanga and Bulacan.

First, and probably the least consequential, Gurnis (1993) and Lithgow-Bartelloni & Gurnis (1997) hypothesized that the deep mantle flow associated with subducting lithospheric slabs pulls down the Earth's surface. They have interpreted Indonesian data as indicating that this cause has dragged down southeast Asia, including the Philippines, about 300 m over the past 30 million years. This equates to only about 0.03 mm/yr. Even if Luzon might experience somewhat higher rates because it is bounded by subduction to the west at the Manila Trench, as well as to the east along the East Luzon and Philippine trenches (Fig. 1), this factor would still be insignificant.

Four other natural phenomena may cause deltas to subside. Two of these are natural consequences of deltaic sedimentation: (1) isostatic sinking as asthenosphere beneath the increasing sediment load is displaced; and (2) autocompaction of the sediment under its own accumulating weight. In the proper geologic setting, any area, including a delta, can be affected by the third and fourth phenomena: tectonic and volcanogenic movements. The Ravenna area of the Po Delta in Italy subsides at a rate of about 2.5 mm/yr, 20% of which is ascribed to sediment loading, 30% to compaction, and 50% to tectonics (Carminati & Di Donato, 1999).

Isostatic subsidence of the Pampanga Delta can be assumed to be relatively minor. If the 7-km thick sedimentary pile beneath the Pampanga Delta has an average specific gravity of 2.4 and was deposited since Miocene time, the average accumulation rate is about 0.3 mm/yr. If deposition caused continuous displacement of asthenosphere with a density of 3.3, the isostatic subsidence rate would have been less than 0.22 mm/yr.

Deltaic sediments, commonly with porosities in excess of 50%, are "autocompacted" by the accumulating overburden as water is squeezed out of it (Rieke & Chilingarian, 1974; Magara, 1976) and, at depths greater than 2 to 3 km, as minerals are dissolved and reprecipitated (Bjørlykke, 1999). Galloway & Hobday (1983) estimated that deposition of the first 1000 m releases more than 2.1×10^4 cm^3 of water per square centimeter of surface area, reducing porosity at the base of the column to about 20%, and that comparable volumes are released by continuing compaction until porosity is minimized at about 10 km of burial. However, Kooi & De Vries (1998) reported that compaction due to sediment loading continues at even greater depths, although much more slowly.

Great thicknesses of muddy sediment are recovered from holes drilled into the bayhead delta plain of Manila Bay. Their natural compaction under continuing accumulations can be expected to contribute to regional subsidence. Logs from water wells indicate that the Pampanga Delta deposits are predominantly argillaceous and, thus, very prone to compaction. We anticipate that relative sea level rise from this cause will prove to be only of the order of magnitude of eustatic rise. The rates should be comparable to those observed on the Po Delta (30% of 2.5 = 0.75 mm/yr), and also those measured in the Holocene deltaic sequence of the Mississippi Delta in southern Louisiana. As determined from radiocarbon-dated peats, compaction rates on the Po and Mississippi deltas range from about 0.9 to 3.7 mm/yr depending on sequence thickness (Kuecher et

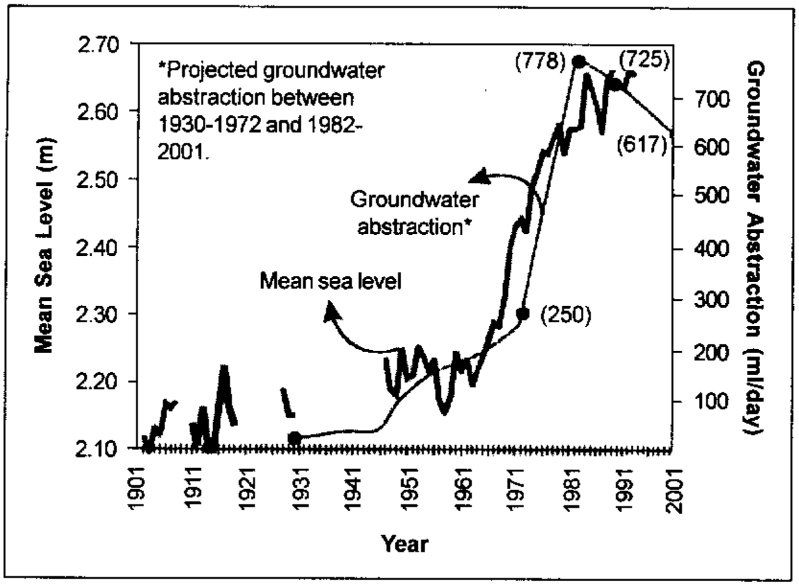

Fig. 7. Mean sea level from tide guage data at Manila South Harbor, and the history of groundwater withdrawal in Manila (Siringan & Ringor, 1998).

al., 1993) and average about 1.8 mm/yr (Penland et al., 1988). In central Louisiana in the Mississippi Delta, Coleman & Roberts (1989) attributed most of the measured 1.6 cm/yr rise in sea level to compaction and subsidence, although groundwater withdrawal likely is a contributing factor.

Faulting is a significant process in many deltas, including the Nile, Rhine-Meuse, and Orinoco (Stanley, 1988, 1990; Warne & Stanley, 1993; Stanley & Goodfriend, 1997; Törnqvist et al., 1998; Aslan et al., 1999). Satellite imagery of the project area reveals six or more lineaments of regional scale, including the one in Fig. 2. Some of these lineaments might be faults experiencing creep with still unknown but possibly substantial vertical displacement; certainly, the accumulating weight of the delta mass east of the igneous abutment comprising Pinatubo and the Bataan volcanoes could contribute gravitationally to such motion. We are continuing to evaluate these lineaments on the ground.

Volcanoes inflate as magmas rise, and deflate as they erupt. After a large eruption of Sakurajima Volcano in Japan in 1914, leveling benchmarks around the volcano that had been occupied in 1895 showed a roughly circular zone at least 60 km wide with more than a meter of subsidence. It was not centered on the volcano itself, but roughly on the center of Kagoshima Bay, an old caldera. Loading, compaction, or gravitational distortion by volcanic products may cause more than a meter of subsidence per year. In Mexico, subsidence has dominated the entire deformation pattern of Colima volcano since a ground deformation network was installed in 1982. Stations that are 1 to 3 km from the summit on average subside nearly 1 cm/km/yr, while stations near the summit subsided 2 cm/yr from 1994 to 1997. Subsidence continued even while lava flowed, and a dome was extruded in 1991 (Murray et al., 2000).

The degree to which Pinatubo lifted and sank prior to and after 1991 has not been measured. However, such movements are probably minor, given the fact that the net subsidence rates over the pre- and post-eruption periods have not been dramatically different.

Anthropogenic subsidence: Groundwater over-pumpage

Many cities located on deltas such as Venice, Bangkok, Tokyo, and Shanghai, have experienced subsidence due to groundwater withdrawal (Dolan & Goodel, 1986). For example, Tokyo subsided from over-pumpage by as much as 4.6 m from 1900 to 1976, with an average rate of 2.7 cm/yr. At Manila's South Harbor, a tide gauge recorded a relative sea level rise of 2.35 cm/yr from 1963 to 1980 (Fig. 7)–an order of magnitude higher than both the local rate from 1902 to 1930, as well as the global average rate (Siringan & Ringor, 1998).

In the Pampanga Delta, our well data document subsidence rates within a few centimeters per year. Reoccupancy of elevation benchmarks by DPWH also closely approximates these rates. How closely they match the subsidence rates derived from the tide-gauge record of the South Harbor in Manila and other localities mentioned above indicates that groundwater extraction is the main cause of subsidence.

In Manila, the tide gauge and groundwater extraction records are closely paralleled by population growth. There, relative sea level rose to about 2 mm/yr from 1902 to the early 1960s, essentially the rate of eustatic rise. The rate increased by an order of magnitude between 1963 and 1980, to 2.35 cm/yr–a trend that correlates very strongly with the increase in groundwater pumpage over the same period. Tide records are unavailable for the Pampanga Delta; however, we argue that correlation between population growth and groundwater extraction holds true for this area as well.

CONCLUSIONS AND RECOMMENDATIONS

The causes of worsening flooding can be assigned to several categories. Of these categories, the most recognized by the public is the region-wide loss of channel capacity due to human encroachment of channels by squatters and fishponds; increased siltation due to deforestation; and clogging from improper garbage disposal. The second category applies to the western Pampanga Delta alone: loss of channel capacity due to increased volcaniclastic sedimentation following the 1991 eruption of Mt. Pinatubo. The third, and most serious, is the rise in local sea level, the most publicized cause being the global rise due to global warming. This, however, is at least an order of magnitude slower than the effect produced by subsidence of the delta deposits, which is greatly accelerated by over-pumpage of groundwater–virtually the only water source for domestic use, and a major source for agriculture. Ironically, these most important causes are those least recognized by the public and by decision makers.

In the short term, the aggravated flooding can be mitigated by the vigorous implementation of government regulations already in existence. Reforestation of the regional mountains would accomplish two things: (1) it would increase the percentage of rainfall that would infiltrate into the soils and aquifers, thus, reducing peak heights and durations of floods; and (2) it would diminish slope erosion and channel silting. Reduction of slope erosion would cause the stream water arriving at the delta to be "underloaded", and they would acquire load by unclogging the delta channels. Removal of accumulated garbage and enforcement of laws prohibiting illegal disposal of garbage would also help mitigate flooding.

Original channel widths should be restored by reclaiming portions illegally encroached upon by squatter housing and by fishponds. The total demolition of fishponds and their dikes is often vociferously called for, but this solution is both economically and politically unfeasible, given the contributions of the aquaculture industry to the nation's food supply and livelihood. We recommend, however, that inhibition of flood flow could be minimized if the fishpond dikes were lowered and their heights restored with porous netting, a practice already widely used in lakes and in Candaba swamp.

Although we advocate channel widening, we must point out that desilting and dredging deeper than one or two meters in channels so close to sea level is costly, ineffective, and actually deleterious, for all it accomplishes is facilitating tidal encroachment and the poisoning of inland groundwater with salt water.

Over the long term, the region must be prepared to cope with continued sea level rise, which is predicted conservatively at a meter over the 21st century, and to minimize the aggravation of this effect by local subsidence due to the extravagant withdrawal of groundwater. One or both of two approaches are indicated. First, the region is entirely bordered by mountains on which small dams could be built to store water, both in surface reservoirs as well as in underground aquifers. Second, if groundwater continues to be a major source of domestic water, it should be regulated by using well-managed central sources instead of a multitude of unregulated small-scale wells.

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