GeoJournal 11.3 245–255

0343–2521/85/0113–0245$1.65

Land Subsidence Caused by Ground Water Withdrawal in Urban Areas

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Abstract: At least eight urban areas in the world have encountered significant economic impact from land subsidence caused by pumping of ground water from unconsolidated sediment. The areas, most of which are coastal, include Bangkok, Houston, Mexico City, Osaka, San Jose, Shanghai, Tokyo, and Venice. Flooding related to decreased ground elevation is the principal adverse effect of the subsidence. Lesser effects include regional tilting, well-casing failures, "rising" buildings, and ground failure or rupture. Subsidence of most of these urban areas began before the phenomenon was discovered and understood. Thus, the subsidence problems were unanticipated. Methods to arrest subsidence typically have included control of ground water pumping and development of surface water to offset the reductions of ground water pumping. Ground water recharge has also been practiced. Areas threatened by flooding have been protected by extensive networks of dikes and sea walls, locks, and pumping stations to remove storm runoff.

Introduction

Unconsolidated sedimentary deposits form one of the world's most prolific types of aquifers. Many cities located over these aquifers have developed them for all or part of their urban water supply. In at least 17 of these cities, the development of local ground water has had an unanticipated impact, land subsidence or gradual lowering of the land surface caused by compaction of the aquifer system. In at least eight of these areas, the economic cost of this type of subsidence has been significant. These cities include Bangkok (Thailand), Houston (USA), Mexico City (Mexico), Osaka (Japan), San Jose (USA), Shanghai (China), Tokyo (Japan), and Venice (Italy) (Fig 1). This article describes these occurrences and reviews the lessons to be learned from this experience.

Land subsidence in urban areas may cause several problems. Potentially the most devastating problem occurs in flat-lying coastal areas where loss of ground elevation may either cause inundation (Fig 2) or increase the potential for flooding by tides and storm surges (Fig 3). When flooding becomes severe enough, expensive flood-control works or even abandonment of the affected land becomes necessary. A second problem may be caused when the magnitude of subsidence is large and the subsidence area is small or narrow. This creates regional tilting that can affect the functioning of structures such as canals and sewers that rely on gravity for their operation. A third problem is well casing failure that decreases and commonly destroys the productivity of water wells. The failure is caused by telescoping of the well casing as the water-bearing formations adjacent to the casing compact. Bonding between the formations and casing is usually sufficient at depths ranging from 50 to 100 m to overcome the strength of the casing, thus causing it to deform with the formations and collapse if deformation becomes great enough. A fourth problem is recognized in cities where the compaction that causes subsidence occurs at shallow depth and where buildings are founded on firm materials beneath compacting layers. Buildings appear to rise above the ground surface when the underlying land subsides in response to the shallow compaction (Fig 2). This may affect utility connections and building access in addition to the structural integrity of buildings. Finally, ground failure or rupture, consisting of tension cracks and reactivated faults, is commonly associated with land subsidence (Holzer 1984). Engineered structures are particularly vulnerable to these failures because surface deformation is very localized.

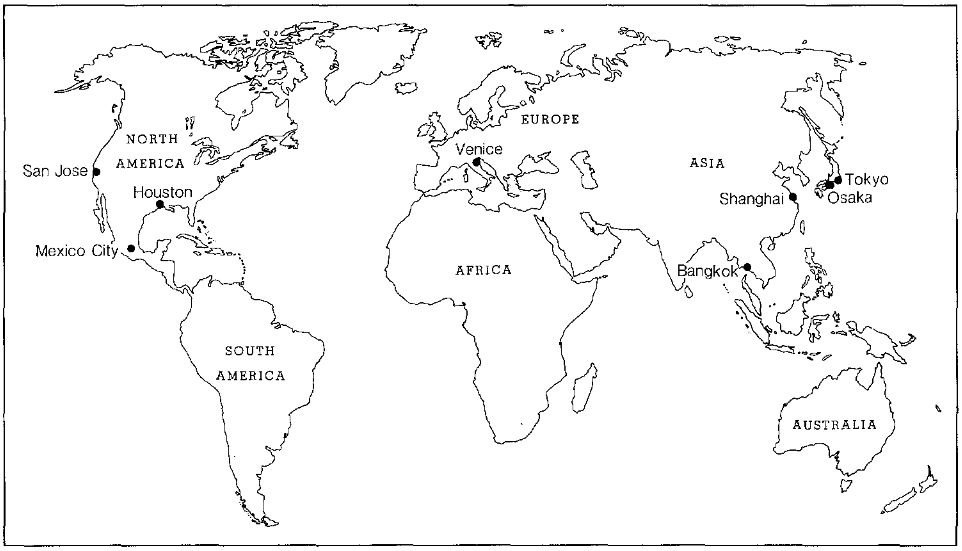

Fig 1 Locations of cities with significant economic impact from land subsidence caused by ground water withdrawal

Concepts

The land subsidence in the urban areas discussed herein is primarily a result of the reduction in pore space of compressible strata in the aquifer system. This reduction of porosity, compaction, is caused by increased effective stresses that are induced by the depressuring of the aquifer system (Domenico and Mifflin 1965). Field and analytical investigations have demonstrated that the compaction can be described in terms of the theory of consolidation which was developed by soil engineers to explain the expulsion of water from soils subject to loading (Lambe and Whitman 1969). Application of this theory has helped to establish a quantitative understanding of subsidence. Two aspects of this theory are particularly relevant to this paper and are briefly reviewed here. They are preconsolidation stress and elastic and inelastic compaction.

Preconsolidation stress is the maximum stress a sedimentary deposit can withstand without undergoing predominantly permanent deformation. It is commonly interpreted to be the maximum effective stress to which the deposit has been subjected in the geologic past. At effective stresses less than the preconsolidation stress, compaction per unit water-level decline is much smaller than that which occurs at effective stresses greater than the preconsolidation stress. If the preconsolidation stress of an aquifer system before ground water development is greater than the effective stress resulting from the existing overburden, the aquifer system is said to be overconsolidated. Thus, with an

Fig 2 Abandoned house in Galveston Bay, Houston, United States (1976). Subsidence has caused bay to encroach over foundation (courtesy of C. W. Kreitler)

Fig 3 Record-high tidal flooding, Doge's Palace in Piazza San Marco, Venice, Italy, on November 4, 1966 (courtesy of Cameraphoto)

overconsolidated aquifer system, initial compaction per unit water-level decline will be smaller than when the preconsolidation stress is eventually exceeded. This causes the rate of subsidence at such sites to increase as water levels decline. Holzer (1981) proposed that many aquifer systems beneath both urban and rural subsidence areas in the US were overconsolidated by an amount equivalent to water-level declines that ranged from 16 to 63m. Overconsolidation has also been proposed for sites at Venice, Italy (Ricceri and Butterfield 1974), and Osaka, Japan (Murayama 1969).

Compaction has both recoverable and irrecoverable components, termed elastic and inelastic, respectively. At effective stresses less than the preconsolidation stress, the elastic component is large relative to the inelastic component. This is particularly characteristic of fine-grained sediment which forms the more compressible part of aquifer systems. At effective stresses greater than the preconsolidation stress, the inelastic component may be two orders of magnitude greater than the elastic component (Helm 1978). An important practical implication of this material behavior is that subsidence at stresses greater than the preconsolidation stress is largely irreversible. Once sediment has compacted, water-level recovery and aquifer repressuring will raise the land only a small fraction of the amount it has subsided.

Case Studies

The following urban areas were selected for review out of many known cases of subsidence because the economic impact of land subsidence in each of them has been significant. The urban areas range from coastal cities, where the cost is associated primarily with real or potential flooding that threatens the existence of all or part of the city, to cities in mountain valleys, where the cost is associated with the effect on design and operation of engineered structures. The precision of available cost figures vary greatly from area to area, but costs for each of the areas are measured in the millions of dollars.

Bangkok, Thailand

Beginning as a trading village in swampy lowlands along the Chao Phraya River, Bangkok today is one of the major cities in SE Asia. In fact, rapid economic growth after WW II has made Bangkok one of the fastest growing cities in the world. Its population has grown from 2 million in 1958 to 4 million in 1973 and to 5.4 million in 1983. In the 1950s, as the surface-water supply failed to keep pace with this population explosion, industries, hotels, and housing developments began to establish their own ground water supplies (Premchitt and Das Gupta 1981). Approximately one third of the metropolitan area water supply presently is derived from ground water. These heavy withdrawals have caused land subsidence that locally exceeds 1 m.

The most severe problem caused by subsidence in Bangkok is flooding. Even small amounts of subsidence pose great danger to the city from tidal flooding because the natural elevation of the area only ranges from 0.5 to 2.0m above sea level. According to Premchitt and Das Gupta (1981), the problem is becoming so severe that if present rates of subsidence continue, the existence of the city itself will be threatened unless flood-protection works are constructed.

Subsidence also has affected buildings founded on deep piles. Bergado (in press) has described damage to structures at the campus of the Asian Institute of Technology. Several buildings partly supported on piles and partly on shallow foundations have suffered differential settlements that cracked, bent, or broke floors and walls. Differential subsidence on campus has also caused longitudinal cracks on asphalt roadways, cracked and uneven sidewalks, breakage of water and sewage transmission pipes, and depressions that create drainage problems. Most of these same problems also exist, in some cases even more severe, in other parts of Bangkok.

Unconsolidated deposits of clay, sand, and gravel constitute the principal source of ground water for Bangkok and its suburbs. These deposits, which are approximately 600m thick, have been divided into eight vertically stacked confined aquifers. The heavy pumpage has caused water levels to decline rapidly from only a few meters below land surface in 1955 to more than 50m in 1982.

Land subsidence in Bangkok was first recognized in 1969, but its cause was not attributed to pumpage of ground water until 1978 (Premchitt 1979). The center of the greatest amount of subsidence coincides with the center of artesian pressure decline ESE of central Bangkok. The present annual rate of subsidence is estimated to be more than 100mm per year, with a total of 1.14m of subsidence occurring between 1940 and 1980 (Ramnarong 1983). The total area experiencing subsidence may be as great as 800km^2. Numerical modeling predicts that land subsidence could be as great as 2m by the year 2000 if strict control of ground water pumpage is not initiated by the government (Premchitt and Das Gupta 1981).

Thailand has developed extensive plans to prevent further subsidence and resultant damage in Bangkok. If implemented, ground water pumpage would be reduced drastically and replaced by imported surface water. In addition, dikes would be built around parts of the city and drainage canals constructed to prevent recurrence of the present flooding. Costs to implement these plans are estimated to range from $300 to $400 million.

Houston, United States

Houston is the center of a large metropolitan area in SE Texas which has heavily relied on local ground water for its municipal and industrial water supply. The area is adjacent to the Gulf of Mexico. The SE part of the area encompasses two major tidal water bodies, Galveston Bay and the Houston Ship Channel. Land subsidence, in places exceeding 2 m, adjacent to these bodies has locally caused permanent inundation and increased the vulnerability of other areas from tidal flooding and storm surges (Fig 4). The Harris-Galveston Coastal Subsidence District (1981) estimated that more than 80 km^2 of low-lying coastal land has been permanently inundated; Kreitler (1977) estimated that a hurricane with a peak storm surge of 5.0 m would have flooded 378 km^2 of land on the W side of Galveston Bay if it had struck in 1976. Even without the occurrence of a major hurricane, Jones (1977) estimated that costs attributable to subsidence were $31.7 million per year from 1969 to 1974. These costs were divided approximately equally between loss of property values and actual flooding damage.

In addition to causing subsidence, ground water withdrawal has reactivated many faults (Fig 5) in the Houston-area (Holzer et al. 1983). More than 150 scarps with an aggregate scarp length of more than 500 km have been recognized; at least 86 of these faults with an aggregate scarp length of 240 km have been documented to be historically active (Verbeek et al. 1979, Verbeek and Clanton 1981, E.R. Verbeek 1982, written communication). The fault scarps aseismically grow in height at an average rate of 10 mm/year. Thus, structural damage accumulates gradually. Damage to structures and loss of property values probably has cost millions of dollars (Clanton and Amsbury 1975).

Ground water in the Houston area is withdrawn from a thick sequence of unconsolidated fluvial sediment. Originally the sole source of the area's water supply, ground water now provides approximately one half of the area's water needs. Ground water development began toward the end of the 19th century. In response to this development, water levels continuously declined from the early 1900s until the 1970s when regulation of pumpage was instituted in part of the region. Maximum declines exceed 100 m.

The regional water-level declines have created one of the largest subsidence bowls in the United States; approximately 12,200 km^2 of land has subsided at least 0.15 m (Gabrysch and Bonnet 1975). Maximum subsidence is estimated to exceed 2.7 m (Gabrysch 1980). Petroleum withdrawal from more than 100 oil and gas fields also may have contributed to subsidence, but only locally over a few fields (Holzer and Bluntzer 1984). Subsidence from ground water withdrawal was of little practical significance for many decades because of the low rate of water-level decline and an overconsolidated condition (Holzer 1981). Public concern over subsidence began to develop in the late 1960s and early 1970s when its magnitude became obvious because of both inundation and the growing susceptibility to storm surges in the coastal area.

In 1975, the Harris-Galveston Coastal Subsidence District was authorized by the Texas State Legislature and given a mandate to arrest subsidence in those areas where subsidence contributes to or precipitates flooding. The district was formed at the instigation of parties affected by flooding in the coastal area and was the result of a series of

Fig 4 Houses damaged or destroyed by storm surge caused by Hurricane Alicia, Houston, Texas (August 1983)

compromises among local government, private interests, and the Texas State Legislature. To accomplish its mandate, the district was given the power to regulate water pumpage from major production wells. Armed with this regulatory authority, the district has been able to reduce pumpage in and near the coastal area and this in turn has caused water level to recover partially in that area (Strause 1984). Records from specially instrumented wells indicate that compaction in the coastal area has been arrested or slowed by the water-level recoveries (Strause 1984). Recoveries of land elevation appears to be negligible relative to the subsidence.

By contrast, institutional efforts have not been made to control land development astride the actively growing fault scarps. Maps of faults in some areas are now available and public awareness of faults has increased, but to date efforts to control land development on faults have been limited to voluntary efforts by builders and developers.

Mexico City, Mexico

Mexico City, one of the world's most populous urban areas, occupies an intermontane valley in central Mexico. The elevation is about 2300m asl. The aquifer beneath Mexico City consists of Plio-Pleistocene alluvial deposits that are overlain by fine-grained lake deposits, volcanic ash, and fluvial sediments. By 1854, more than 140 free-flowing wells had been drilled into the aquifer (Poland and Davis 1969). Despite efforts to augment the valley's supply with imports beginning in 1952, growth of water demand has caused water-level declines to continue.

The most serious problem caused by the subsidence in Mexico City derives from the unusually large magnitude of subsidence; the maximum amount is slightly more than 8.5m (Figueroa Vega 1977). This subsidence is not uniform within the valley and has adversely affected the gradients of sewers and thereby increased the potential for flooding by sewage. Until the recent construction of a sewer tunnel, sewage water had to be pumped to the main discharge channel, which was below the general elevation of the city (Figueroa Vega 1977). A second problem has been with structures that are built on piles founded on firm layers within the compacting aquifer system. This type of foundation is necessary because of the compressibility of subsoils in Mexico City and the potential for differential settlements caused by the weight of structures (Fig 6). As the ground beneath structures built on piles subsides in response to water-level declines, the structures appear to rise above the land surface (Fig 7). This disrupts utility service and requires maintenance of adjacent sidewalks and access structures. Another problem, localized in Etchegaray, NW of Mexico City, is surface faulting that has damaged houses and other structures including a school. The two fault scarps there are increasing in height by aseismic creep and appear to have formed contemporaneously with the ground water withdrawal. Although the mechanism of faulting has not been rigorously investigated, the aseismic growth of the scarps and the recency of formation suggest a relation to ground water withdrawal.

Fig 5 House on Billings Street damaged by 0.4m historical vertical offset across the Long Point fault, Houston, USA (June 1980). Scarp, down to the right, passes through garage and patch in road

Mexico City also provides a rare constructive example of land subsidence (Herrera et al. 1977). Land subsidence was intentionally induced in Lago de Texcoco, a dry lake bed, to create four 8 m deep depressions for water impoundment. Special wells were drilled to produce the design subsidence.

Subsidence of Mexico City probably began before 1891 when the first precise leveling surveys were conducted. Thus the absolute maximum subsidence is unknown. The maximum measured is 8.5 m, as was previously noted. Rates of subsidence in the central part of the city, which has the longest record of relevelings, have ranged from 0.045 to 0.460 m/yr. Rates have been decreasing since about 1951. Approximately 225 km^2 of land has subsided.

Concern about ground water in Mexico City has focussed on the overdraft problem. Continued urban growth has severely stressed the city's water supply. Thus, institutional efforts have focussed on augmenting water

Fig 6 Extreme differential settlement of the Capuchinas Church (right) adjacent to the Basilica of our Lady of Guadalupe, Mexico City, Mexico, caused by weight of the basilica and variable thickness of underlying compressible strata (April 1977)

Fig 7 "Rising" building in Mexico City, Mexico (April 1977). Building is built on piles that are founded on firm strata partially beneath compacting interval. Land surface has settled beneath and around building. Note elevated curb of building and buckled sidewalk supplies. Concerns about subsidence have led to the development of predictive models, so that the effect of subsidence on new structures can be accommodated by engineering design.

Osaka and Tokyo, Japan

Subsidence in Japan has been recognized in at least 60 locations. Yamamoto and Kobayashi (in press) report eight areas where more than 100km^2 of land sank at a rate greater than 20mm per year or total subsidence was greater than 0.2m. Two of the primary areas of subsidence are at Tokyo and Osaka, although the problem is essentially under control at present owing to surface water importation.

Following WW II, the rapid industrial development in Japan led to extensive development of ground water for industrial, domestic, and agricultural supply. Ground water provides one-third of all water used in Japanese cities. Its use for air conditioning utilizing the heat pump principle and for melting of snow is expected to increase. In addition, ground water is pumped for recreation purposes, hot-water spas, and in conjunction with mining of natural gas.

As previously noted, subsidence has been most extensive in Tokyo and Osaka. At Tokyo, more than 3,000km^2 of land subsided due to ground water pumpage. Maximum subsidence was about 5m. An area containing around 10 million people would be flooded if an extensive system of levees to hold back the sea had not been built (Fig 8). At Osaka, an area of over 500km^2 subsided from 1935 to 1970. Maximum subsidence was about 3m. As of 1970, approximately 25% of Osaka was below mean low-tide level and over 50% was below high-tide level. If it were not for extensive protective works, including locks or sea gates, these areas too would be flooded. At times of a major typhoon as much as 80% of Osaka would be flooded without such protection. Storm surges caused by typhoons can still cause considerable flooding even with the many levees and flood walls. To minimize damage from these surges, special canals, locks, and huge pumping stations have been built. In Osaka, for example, protective work as of 1970 included over 160km of flood walls and levees, 80 pumping stations, 40 locks, and 500 flood gates.

Efforts to control subsidence have been extensive, taking place mainly since release of a report of the Japan Resources Council in 1974. After that the government adopted an "Industrial Water Law" and a "Building Water Law" for the legislative regulation of ground water pumpage for industries and for air conditioning in buildings. The 1974 report also recommended use of ground water recharge and construction of underground reservoirs. Since 1975, four areas have been designated for control under the industrial law and ten sites have been controlled under the building law. Recently there have been fewer designated sites under the building law because the type of air contioning equipment has changed from a type using high-consumption of ground water to a circulating type. To encourage use of surface water instead of ground water, dams, estuarine barriers, and canals have been constructed. Also since 1975, ground water recharge has been carried out using funds collected as fees from ground water users. In addition, over 200 ordinances by local and regional

Fig 8 Dike protecting subsided area from inundation by river, Tokyo, Japan (September 1969). River level is at second-floor level of houses. Frames under construction will support roadway over river

governments have induced improved utilization of ground water in order to reduce the threat of subsidence. Through all of these control measures, land subsidence is essentially under control in Tokyo and Osaka. Subsidence in other areas in Japan is still increasing and new subsidence areas are developing. Therefore, the Resources Council is recommending even more rigid ground water control measures and more artificial recharge.

San Jose, United States

San Jose is part of a former agricultural area, the Santa Clara Valley, which has undergone extensive urban development since WW II. The urban area is on the S margin of San Francisco Bay in N California. As a result of heavy ground water withdrawal, land adjacent to S San Francisco Bay has subsided from 0.6 to 2.4m (Poland 1969). The economic impact from subsidence has been smaller than it might have been because urban development near the shoreline has been modest. Most of the coastal area consists of marshlands that constrained residential and commercial development except for salt evaporation ponds. The principal cost associated with subsidence has been for construction and raising of levees to protect the modest development that has occurred near the bay (Fig 9). Poland (1977) estimated that approximately $9 million was spent on levees at the ends of depressed stream channels in order to spare 44km^2 of land from inundation; an unknown amount was spent by a major salt company on levees to preserve 78km^2 of salt evaporation ponds. In addition to costs associated with loss of elevation, more than $4 million was spent to replace or repair water wells casings which were damaged by compaction in the aquifer system (Roll 1967). The gross costs of subsidence probably have been $15–20 million (Poland 1977), although Fowler (1981) estimated that direct costs attributable to subsidence were more than $130 million when brought to 1979 values. His estimate was dominated by an estimated $103 million that would be required to construct a new levee system to improve protection of bay-front lands from salt-water flooding.

Ground water is pumped in the Santa Clara Valley from an unconsolidated alluvial aquifer. Water levels began to decline about 1898 but were temporarily arrested in the early 1940s by man-induced ground water recharge and reduced pumping caused by abnormally high rainfall. After the end of WW II, industrial and urban activities began to supplant agriculture as the principal activity in the valley and water levels renewed their decline. These declines continued until the 1960s when comprehensive water resource management was implemented.

Subsidence caused by ground water withdrawal has affected more than 595km^2 of land in the Santa Clara Valley; approximately 260km^2 of land has subsided at least 1 m. The maximum subsidence is 3.9m from 1912 to 1969 in the city of San Jose. The history of subsidence closely follows the history of water-level decline. Particularly noteworthy was the temporary arresting of subsidence in conjunction with the water-level recoveries in the early 1940s; the subsidence resumed after WW II when water levels renewed their decline. Subsidence was stopped in the late 1960s when water levels recovered after reductions of pumping.

Fig 9 Alviso Yacht Club, south end of San Francisco Bay, San Jose, United States (August 1980). Area has subsided approximately 2m and is protected from inundation by levee shown in photograph. Note water level behind levee

The halting of subsidence in the Santa Clara Valley was collateral to the effort to curtail the ground water overdraft problem which threatened the long-term availability of water in the valley. The institutional efforts began in 1929 when the Santa Clara Valley Water District was chartered under California state law to assume responsibility for mitigating the overdraft problem. The first remedy was to enhance recharge around the margins of the valley by construction of flood retention structures along major stream channels. Continued growth of the demand for ground water eventually required the district to import water. Major imports were obtained via the South Bay Aqueduct, beginning in 1965. By imposing a tax in 1964 on ground water pumpage that removed the economic incentive to use ground water, ground water users were encouraged to switch to the imported surface water. This switch led to the arresting of subsidence in the 1960s.

Shanghai, China

Shanghai, the largest industrial city of China, is situated on the delta of the Yangtze river in the plains area of E China. Between 1921, when subsidence was first recognized, and 1965, parts of Shanghai had subsided 2.63m. An area of approximately 121 km^2 subsided 0.5m or more (Luxiang and Manfang 1984). Because the average elevation of the city is only 4m above mean sea level, flooding caused by heavy rains and tides became a frequent occurrence in parts of the city, particularly dockyard areas. In the 1950s, 100km of dikes were built to protect areas from tidal flooding and pumping stations were installed to remove flood waters from rainstorms.

Ground water beneath Shanghai is pumped from a 300m thick sequence of Quaternary sediment. The upper 150m consist of interbedded littoral clay and silt and the lower 150m consist of alternating fluvio-alluvial sands and lacustrine clays. The sediments have been subdivided into 13 layers, including eight clayey layers, one shallow water table aquifer, and five confined aquifers (Guangxiao and Yiaoqi, in press). Compaction occurs mainly in three soft compressible layers in the upper 70m of the sediments.

Shanghai's first deep well was drilled in 1860. The main uses for ground water were for humidifying the air, industrial washing and cooling, and domestic purposes. Ground water pumpage slowly increased until 1965 when a recharge program was instituted to arrest the subsidence. The greatest subsidence occurred from 1956 to 1959 when the annual rates were locally as great as 98mm.

Although land subsidence was first observed early in 1921, serious investigations of the problem were not undertaken until after the revolution in 1949. The maximum subsidence from 1921 to 1949 was 0.64m. The rate of subsidence increased after the revolution as industrial pumpage increased.

Remedial measures were instituted by the government starting in 1963 to bring the subsidence under control. The principal measures have been ground water recharge and reduction of pumpage. Deep wells used by factories for cooling purposes in the summer are now used for recharge during the winter months. Recharge during the winter has lowered ground water temperatures and thereby reduced the volume that needs to be pumped for cooling during the summer. Recharge has also permitted greater use of deeper and less compressible aquifers that formerly contained water that was too warm for cooling. In addition, restrictions have been imposed on the amount of water that may be withdrawn in the winter. Ground water withdrawal in 1965 was only 42% of that in 1963. As a result of these control measures, water levels have recovered and the rate of land subsidence has slowed down. Local scientists and engineers apparently believe that such control measures are producing good results in bringing the subsidence to at least acceptable limits.

Venice, Italy

The historic, canal-lined city of Venice is situated in a crescent shaped lagoon which connects to the Adriatic Sea. This coupled with its low mean elevation, 1.1 m (Gatto and Carbognin 1981), have made the city particularly susceptible to flooding. In fact, the historical record contains repeated references to abnormally high tide levels which are known locally as *acque alte* (high waters). Their frequency, however, began to increase in the 1960s and culminated in a record high level on November 4, 1966, which submerged Piazza San Marco under more than one meter of water (Fig 3). Of the 18 tides from 1916 to 1982 that exceeded heights above mean sea level of 1.3m, 13 have occurred since 1959. The increased incidence of floodings was partially attributed to man-induced subsidence, and it prompted concern for the very survival of Venice.

The susceptibility of Venice to flooding and its sensitivity to even small amounts of subsidence are illustrated by the following statistics relating flooded area to tide heights (Avanzi et al. 1980). A tide with a height of 1.3m covers 62% of the city with water. A decrease in tide height from 1.3 to 1.2m reduces the area of the city covered by flood waters to 33%. For tides of 1.1 and 1.0m, the area drops to 15% and 5%, respectively. Thus, subsidence of Venice as small as 0.1 m has a large impact on the area susceptible to flooding.

As will be discussed later, ground water pumping is only partially responsible for the subsidence of Venice, but during the 1950s and 1960s, it was the dominant cause. Withdrawals are concentrated at the industrial center of Porto Marghera on the mainland, 7km from Venice (Gatto and Carbognin 1981). The aquifer system tapped there is continuous between Porto Marghera and Venice. It consists of a 350m thick sequence of alternating sand and silt and clay layers. Regional water-level declines began about 1930. The rate of decline in Venice was greatest from 1950 to 1970. Maximum declines were approximately 20m at Porto Marghera and 9m at Venice and occurred in 1969. A 60% reduction of pumpage, which began in 1970, has caused water levels to recover to the pre-1930 levels.

The subsidence of Venice relative to mean sea level is the combined result of three processes: man-induced compaction, eustatic rise of sea level, and natural geologic deformation. Gatto and Carbognin (1981) estimated that from 1908 to 1980, each component contributed 10, 9, and 3cm, respectively, to the total 22cm subsidence of Venice. During the period from 1952 to 1969, when the rate of water-level decline was greatest, man-induced subsidence accounted for 70% of the total subsidence (Carbognin et al. 1977).

Relief from the man-induced component of subsidence was provided by an aqueduct from the Sile river that began supplying surface water to the Porto Marghera-Venice area in 1969. This caused a reduction of 60% in the number of active wells in the industrial area from 1969 to 1975. In addition, well drilling was prohibited in the Venetian Plain (Carbognin et al. 1977). These efforts resulted in water-level recoveries that have arrested the land subsidence.

The efforts to deal with the flooding problem in Venice have been spearheaded by the Italian Parliament through the Committee for the Safeguard of Venice under the aegis of the Ministry of Public Works. These efforts were initiated following the severe flooding in November 1966. Technical investigations and scientific research on subsidence have been organized by the National Research Council of Italy.

Discussion

Although many cities around the world have been affected by land subsidence caused by withdrawal of ground water beneath urban areas, only eight have suffered significant economic impact. Ground water development in most of these areas antedated discovery and general understanding of subsidence caused by ground water withdrawal, which did not come until the 1940s. Thus, most of these areas had been subsiding for several decades before the subsidence phenomenon was understood and its practical significance, principally flooding, was recognized. Repeated geodetic measurements in several of these cities, including Mexico City, San Jose, Shanghai, and Tokyo, in the 1920s indicated subsidence, but the cause of the subsidence was neither immediately nor correctly diagnosed. Despite the early detection, concern for the practical significance of the subsidence also was not forthcoming, but awaited the manifestation of flooding problems.

All of the urban areas except Mexico City are coastal and thus are particularly vulnerable to loss of elevation. Not only have parts of these areas been submerged, but the susceptibility to flooding of other parts has been increased. The principal hazard in the latter situation is from high tides and storm surges. For two areas, Bangkok and Venice, which have mean elevations above sea level of less than two meters, subsidence has threatened their very survival.

Because the loss of elevation is essentially irreversible, protection of land from flooding requires construction of permanent flood control structures such as dikes. These structures are only temporary solutions unless subsidence is arrested. To accomplish this, water-level declines must be arrested. Most areas have resorted to this solution by combinations of direct controls on ground water pumping, providing cost-competitive surface water to users, and ground water recharge.

Will new urban areas be added to the list in the future? Quite possibly. Although ground water hydrologists are knowledgeable about land subsidence as a potential consequence of ground water development of compressible aquifers, understand its physics, and can predict its magnitude given adequate field data (Helm 1984), its control requires an institutional response. The problem is akin to Garrett Hardin's (1968) "Tragedy of the Commons" because there is no incentive to the individual user of ground water to curtail pumping. Unless alternative water supplies are provided or pumping of ground water is controlled either by taxation or regulation, economic incentives usually encourage use of local ground water.

Acknowledgements

The authors are grateful to Joseph F. Poland and Robert F. Yerkes for their reviews of the manuscript. Laura Carbognin reviewed the section on Venice.

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