Case History No. 9.8. Mexico., D. F., Mexico, by Germán E. Figueroa Vega, Comisión de Aguas del Valle de México, Mexico, D., F.

9.8.1 GEOLOGY

Mexico City is located in the southwestern portion of the Valley of Mexico. The general geological features of the zone are shown in Figure 9.8.1. in which it may be seen that the most ancient outcrops, in the upper part of the western and northern ranges of the zone, are andesitic and dacitic formations of the middle Tertiary, overlain on their slopes by volcanic and alluvial formations of the upper Tertiary and Quaternary (Comisión Hydrológica de la Cuenca del Valle de México, 1961b).

The southern range is almost completely covered by Quaternary basaltic emissions and the flatter portion of the city is constituted by Quaternary lacustrine clays. These clays overlie Quaternary clastics that constitute the aquifer whose overdraft has caused the subsidence. The definition of the symbols which appear in Figure 9.8.1. is given in Table 9.8.1.

The clayey formation has a variable thickness from 0 to 50 m. with some intercalations of fine sands and silts, void ratios up to 15 and water contents up to 650 per cent. As a consequence, its shearing strength is very low and its compressibility very high.

The aquifer contains thick strata of gravel and sand of good permeability. Wells are generally of high yield (180 to 360 m^3/hr or more) with specific capacities ranging between 18 and 36 m^3/hr/m and more.

The mechanical properties of Mexico city clays, especially their low shearing strength, make it necessary to carry out special soil mechanics studies practically in all types of foundations.

In general, foundations by continuous slabs are possible only in buildings with no more than 4 or 5 stories. in any building higher than this, it is necessary to resort to the use of compensated foundations which present difficulties due to stability problems in slopes and in bottoms of excavations. An easier alternative is the use of friction or point piles. In this way it has been possible to construct buildings up to 42 stories high.

Because of similar problems in the construction of sewage tunnels and their shafts, it has been necessary to use shields and compressed air and, in some cases, very special construction methods.

The Mexico City clays have been studied from a mineralogical standpoint by nuclear spectrography, electronic microscopy, and interchange of cations and thermic differential analysis to determine their composition. Their approximate composition is 80 per cent montmorillonite and 15 per cent kaolinite, with some beidellite, illite, and halloysite. The clayey materials are mixed with 2 to 20 per cent of the total weight of solids (mixtures of sands and fossils) to which some investigators attribute the elastic properties of clays (Marsal and Mazari, 1959).

9.8.2 HYDROLOGY

The portion of the valley which contains the City of Mexico has an area of approximately 958 km^2. The annual precipitation ranges from 60 mm in the lower zone to 1300 mm in the higher zone, with an average on the order of 890 mm per year.

The potential evaporation ranges between 1900 mm per year for the lower zone and 900 mm for the higher zone, with an average of the order of 1300 mm.

The mean runoff of the period 1948-60, within the 958 km^2, including the urban area of the city, was 20.5 per cent and in the nonurbanized area (238 km^2), 14.6 per cent (Comisión Hydrológica de la Cuenca del Valle de México, 1963).

Figure 9.8.2, which shows a north-south stratigraphic profile of the city, and Figure 9.8.3, which shows an east-west stratigraphic profile (Marsal and Mazari, 1959), allow us to appreciate that the permeable outcrops are in the slopes of the mountains. This is why those zones are the main recharge areas of the aquifer under exploitation. In spite of this, infiltration may occur in the clayey zone as happens in the northern part of the city which has

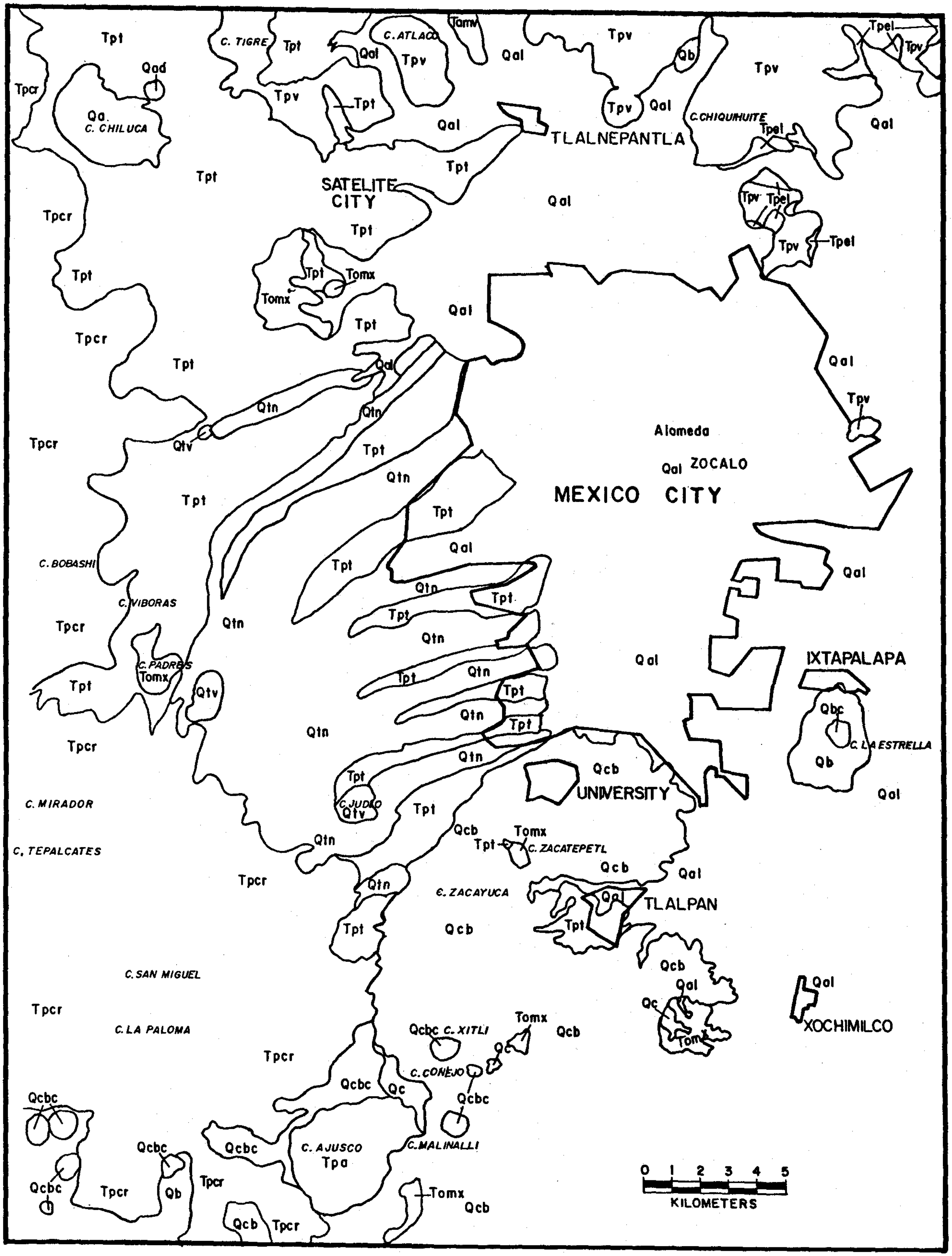

Figure 9.8.1 Geologic map (after Comisión Hydrológica de la Cuenca del Valle de México, 1961).

Table 9.8.1 Geological symbols and units.

Qal	Alluvials, lacustrine and clastic deposits	
Qb	Interstratification of lavas and tuffs	
Qbc	Ash cones	Quaternary basalt-andesite volcanic series
Qad	Andesite lava domes	
Qa	Andesite lava	
Qcb	Interstratification of lavas and basalt tuffs	Quaternary Chichinautzin volcanic series
Qcbc	Ash cones	
Qtn	Nuees ardents, peleans, lahars,	
Qtv	Fluvial conglomerates, pumice horizons, soils and tuffs	Quaternary Upper Tarango formation
Tpt	Nuees ardents of ashlar stone type, pumice horizons, soils and tuffs	Tertiary Lower Tarango formation
Tpel	Eluvial deposits	
TpV	Undifferentiated volcanic rocks Tepozotlan range andesite. Guadalupe range dacites. Range deposits.	Tertiary volcanic rocks
Tpa	Ajusco andesite	
Tpcr	Andesite series of the Cruces range.	
Tomx	Undifferentiated volcanic series of the Xonchitepec range.	

a similar stratigraphy. Here there is a solar evaporator for the industrial exploitation of brines. Water remains all year on the surface and it has been determined by careful balances that the yearly infiltration loss is 20 cm. As it is estimated that in the city the fresh water loss in the net leakage is almost 30 per cent, there may be a local infiltration on the order of 2 m^3/s or more.

It is rather difficult to estimate the historical development of local pumpage because, even now, no flow measurements are made in most of the wells.

Taking into consideration the existent fractional information and the reported population at different dates, it has been estimated that the extraction, which began around 1850, is presently on the order of 12 m^3/s. The approximate development is shown in Table 9.8.2 (Figueroa Vega, 1973a and 1977).

In regard to deep piezometric developments, there are similar problems, since their detailed measurement has been made only during the last 10 years. Notwithstanding, from existent data in the Well Register it has been possible to reconstruct partially the evolution as shown in Figures 9.8.4 and 9.8.5. Evolutions prior to 1948 may be estimated only by the fact that, according to old local drillers, many wells within the Lake zone of the city were still flowing wells at the beginning of this century. The water table has remained nearly constant 1 to 2 m below the land surface throughout the period of ground-water development.

9.8.3 LAND SUBSIDENCE

The subsidence of Mexico City is one of the most remarkable cases in all the world.

The phenomenon, which began during the past century, was discovered casually as a result of a polemic about the subsidence of the gates of San Lazaro, at the beginning of the main sewage channel of the city.

In February 1925, Roberto Gayol, author of the project of the sewage net of the city and director of its construction, demonstrated before the Association of Engineers and Architects of Mexico that the problem was just the result of the general subsidence of the bottom of the valley, presenting as evidence two precision levelings, made in 1877 and 1924, of a monument located near the Cathedral (Gayol, 1925). Gayol attributed the phenomenon to the effect of the recently built drainage system.

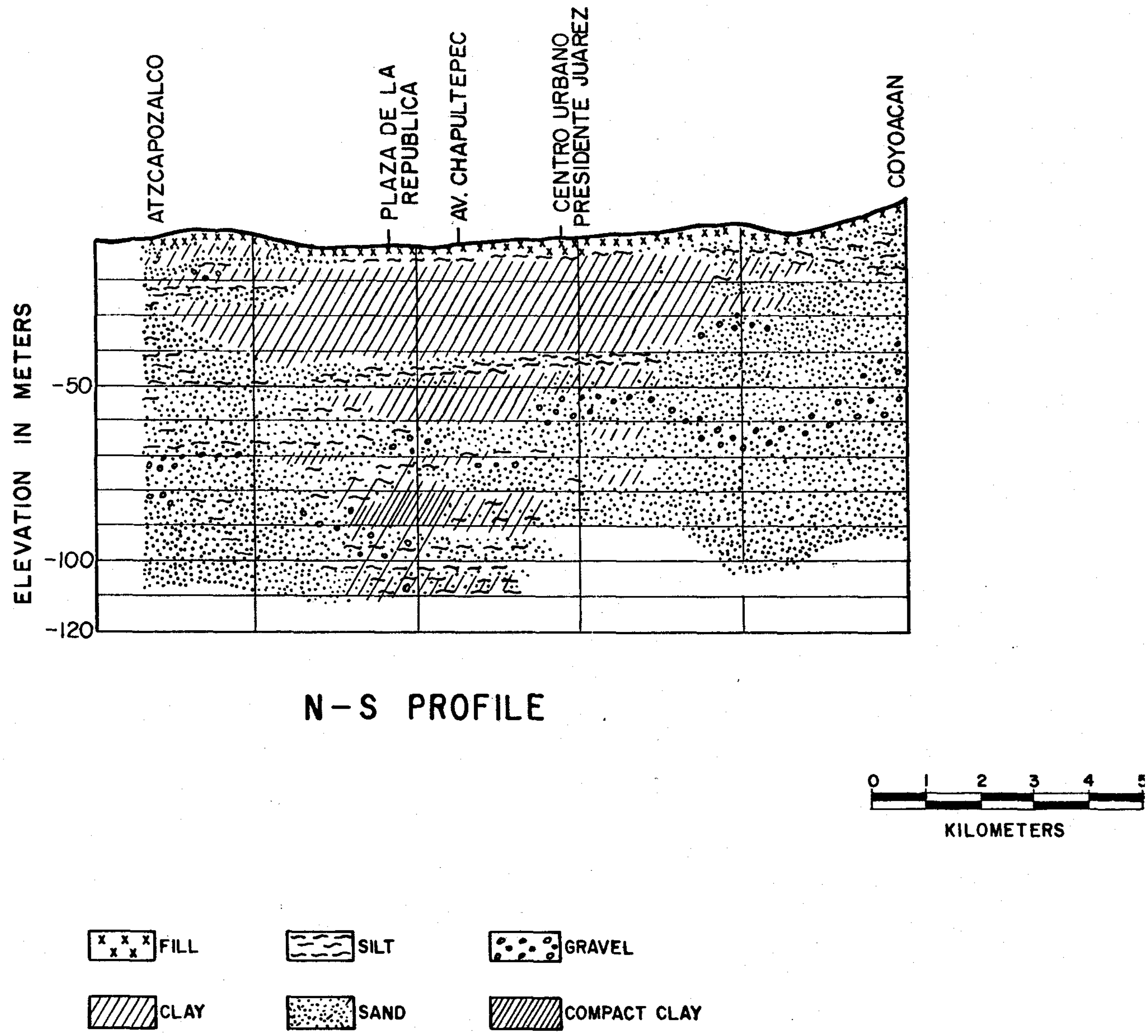

Figure 9.8.2 North-south geological profile (after Marsal and Mazari, 1959).

In spite of the importance of the discovery, 23 years elapsed before Nabor Carrillo demonstrated that the main cause of the subsidence was the extraction of ground-water by wells for municipal use (Carrillo, 1948).

Carrillo, using a profile consisting of an aquifer overlain by clayey strata and assuming a lineal distribution within the clays for the neutral pressures at the beginning and end of the process of consolidation, found the evolution of neutral pressures in the aquifer, corresponding to a constant subsidence velocity of the surface of the clay (Carrillo, 1948).

After that, other investigators continued developing these ideas (Marsal, Hiriart, and Sandoval, 1951). By collecting all the available information regarding precision levelings and mechanical properties of the local clays, they reconstructed the history of the subsidence and made a first prediction about its probable future total magnitude, as shown in Figure 9.8.6 (Marsal, 1952).

At the same time, bench marks and piezometric stations were installed for the observation of subsidence and the evolution of the neutral pressures at different depths. In accordance with the consolidation theory, the neutral pressures are directly related with the phenomenon,

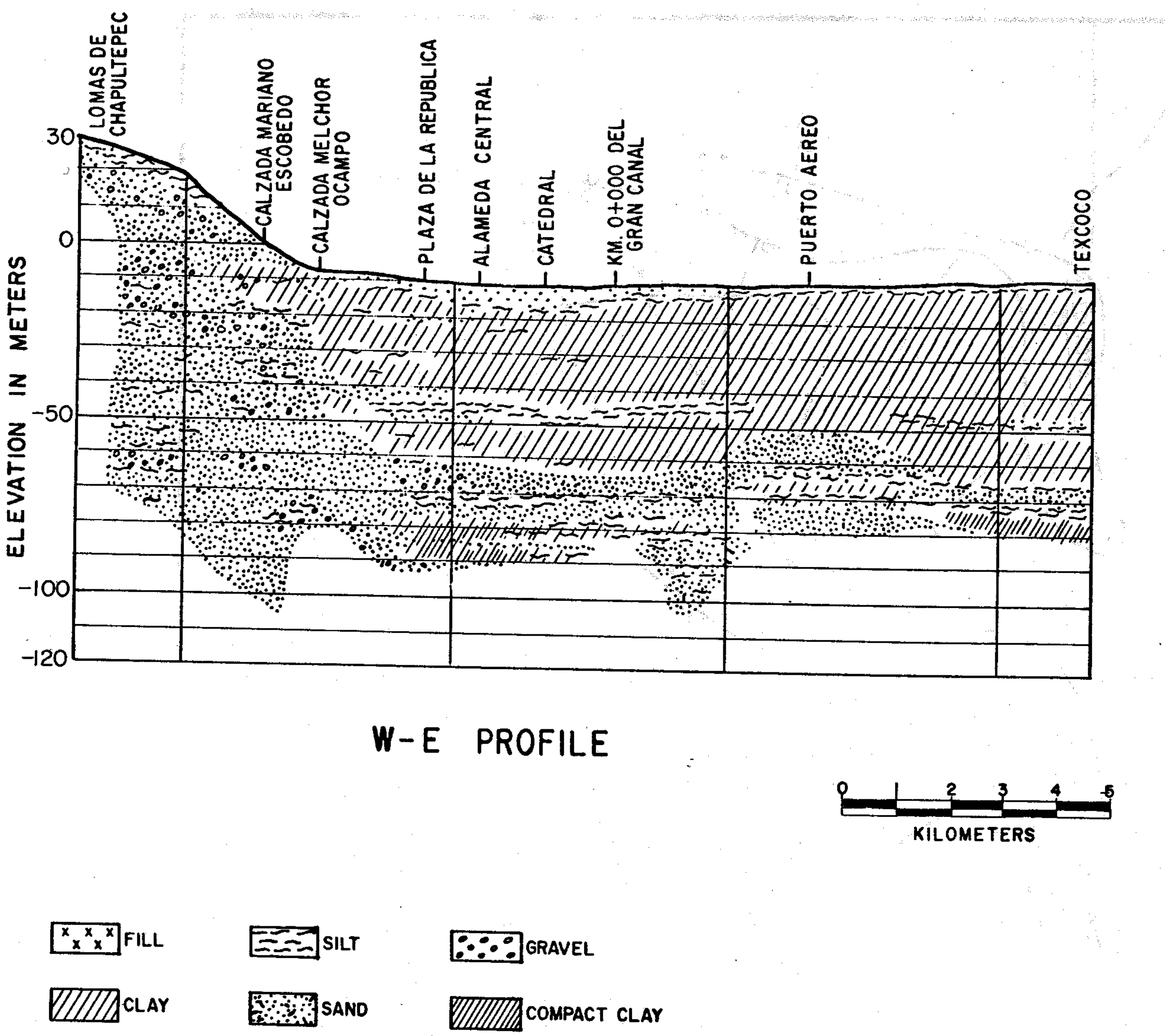

Figure 9.8.3 East-west geological profile (after Marsal and Mazari, 1959).

Table 9.8.2. Orders of magnitude of ground water pumpage in Mexico City.

Year	Pumping Rate (m3/s)
1860	0.0
1910	0.5
1930	1.5
1940	6.0
1950	9.0
1960	9.0
1970	9.0
1974	12.0

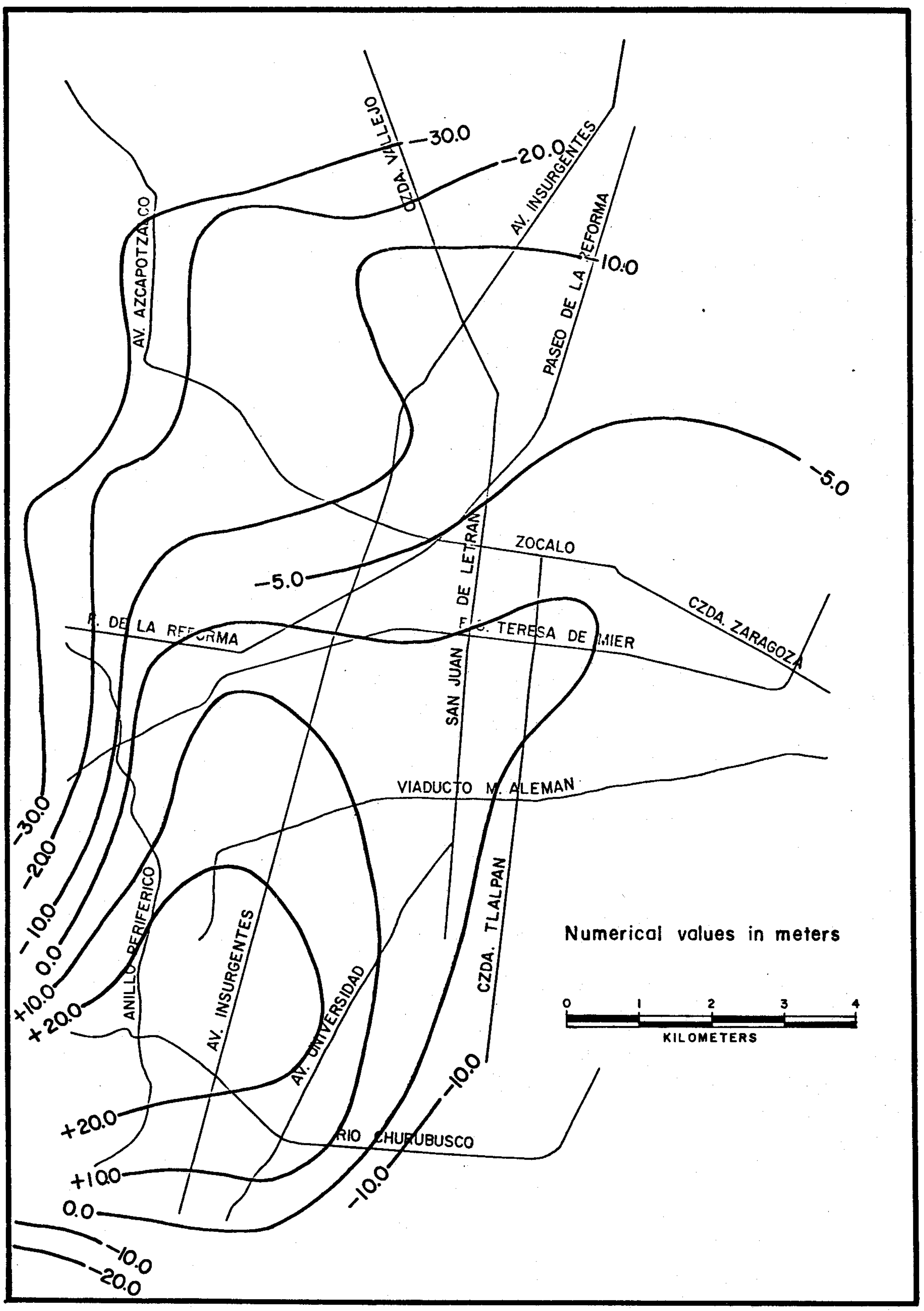

Figure 9.8.4 Change in ground-water level, 1948-1975.

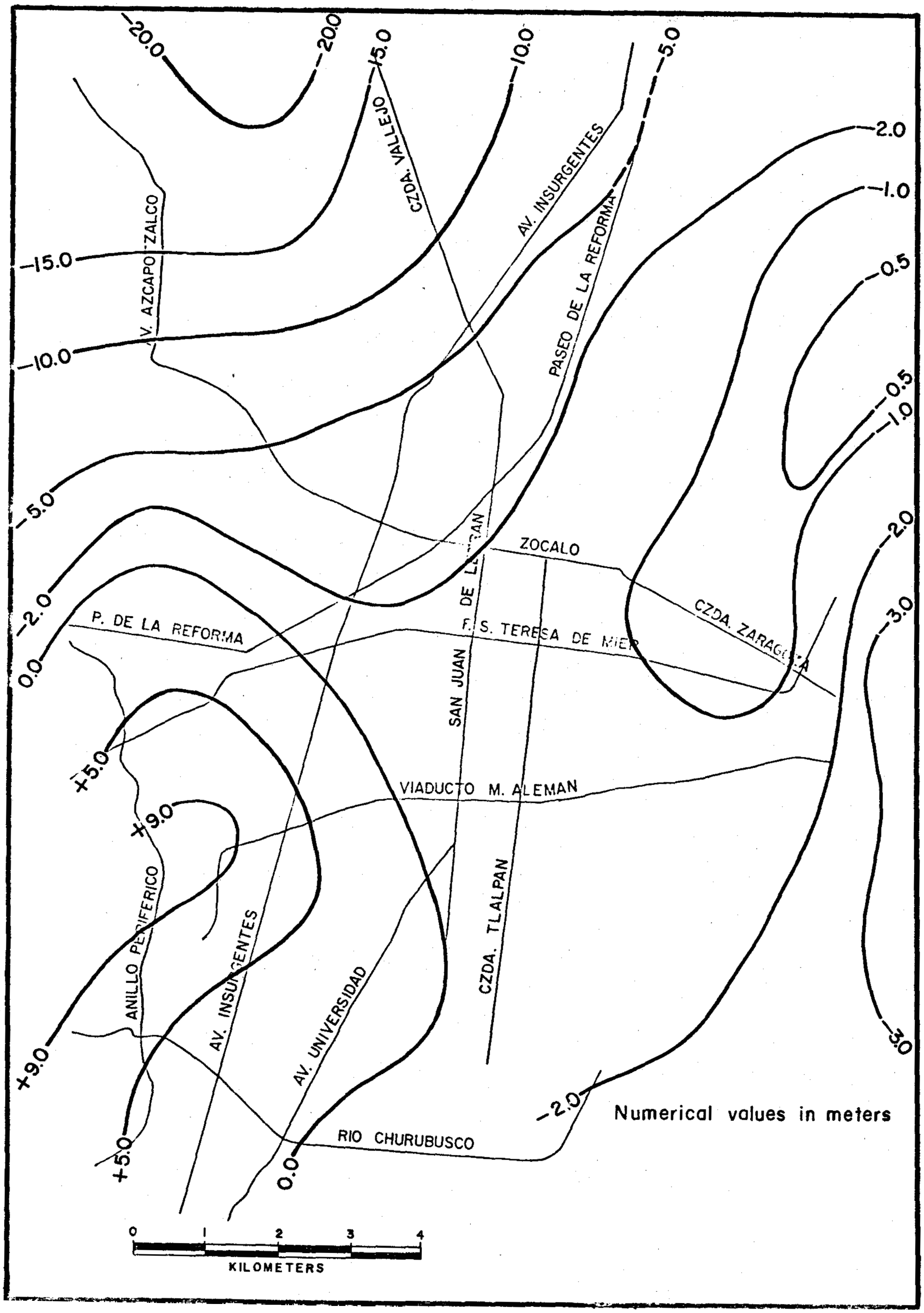

Figure 9.8.5 Change in ground-water level, 1969-1975.

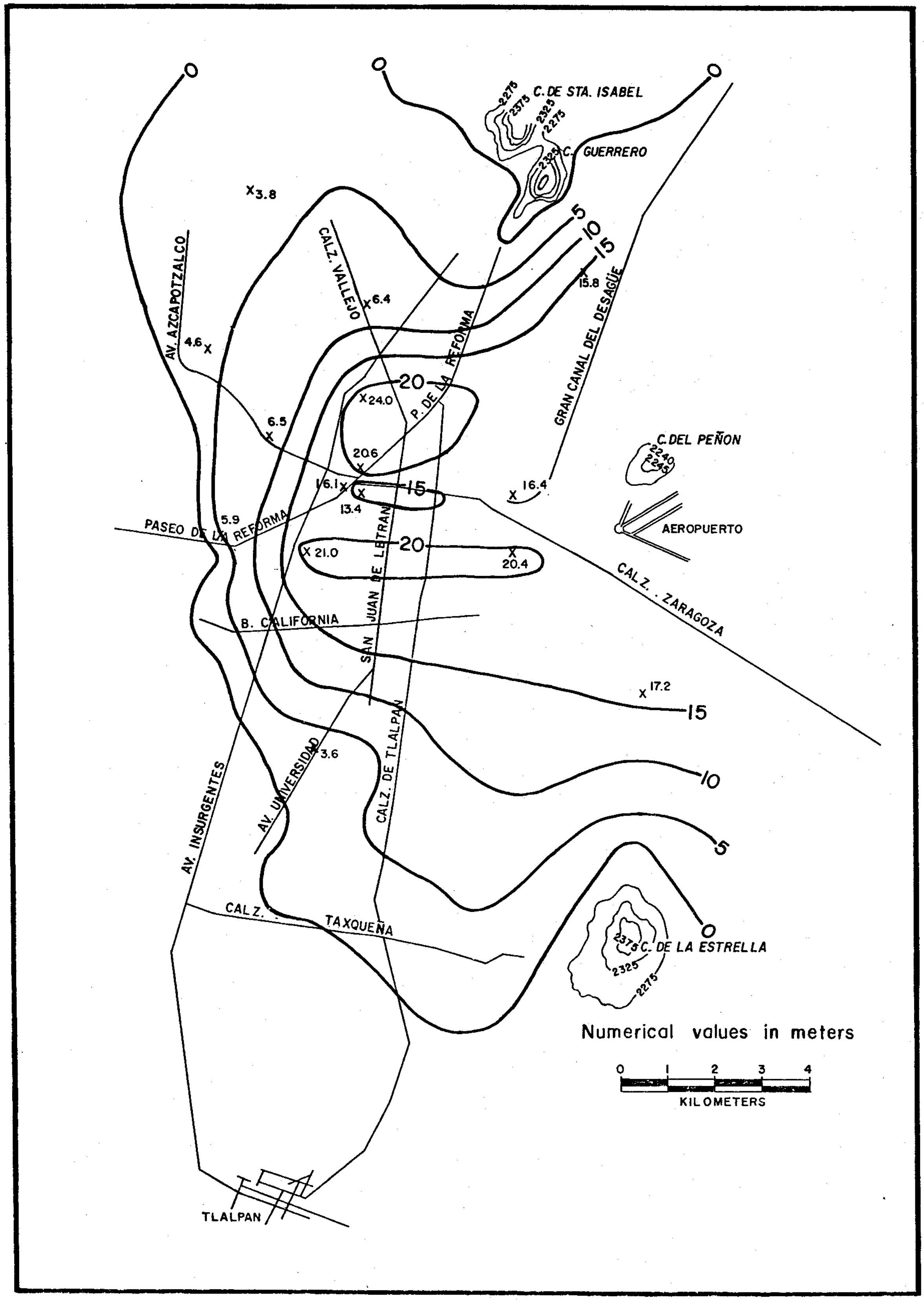

Figure 9.8.6 Potential upper limits of subsidence (after Marsal, 1952).

since their reduction causes a load transfer to the soil structure, with its consequent reduction of volume and resulting subsidence of its surface.

As for the mechanical properties of the clays in the city, a huge quantity of information has been collected, giving rise to a statistical presentation of the existing data and to a stratigraphic zoning of the city, which may be seen in Figure 9.8.7 (Marsal and Mazari, 1959).

Here, in the presence of three main zones, may be noticed: the Hills Zone, located over tuffs of low compressibility, the Transition Zone, and the Lake Zone, located over clays of high compressibility.

In 1954 the Hydrological Commission of the Valley of Mexico, which is now the Water Commission of the Valley of Mexico, took charge of the observation of the subsidence, adopting for this the already established practices. Since then more piezometric stations have been installed, and new precision levellings performed, as well as other observations to be mentioned later in this paper.

The data relative to the above have been published previously (Comisión Hydrológica de la Cuenca del Valle de México, Boletín de Mecánica de Suelos Num. 1, 1953; 2, 1958; 3, 1961a; 4, 1965; 5, 1967; 6, 1970; and 7, 1975).

Accordingly, the subsidence of Mexico City has been known since 1891 for the old part of the city and since 1952 for the total city area.

For the purposes of the present paper, some other figures have been selected (Figures 9.8.8 through 9.8.11) showing, for the old part of the city, the subsidence during the periods 1891-1952, 1952-1973, and 1891-1973, and for all the city during the period 1952-1973. In the same way, Figure 9.8.12 shows the observed subsidence through time of several selected points.

On the other hand, Tables 9.8.3 and 9.8.4 show the mean velocity of subsidence in the old part of the city and in the total area for different periods. The general evolution of subsidence in Mexico City can be visualized through the maps, graphs, and tables included herein. It may be seen that at some places it has almost reached 9 metres. Figure 9.8.12 shows the general trend of subsidence, which has evolved as an inverted "S" of asymptotic nature, with a remarkable diminution in recent years.

In addition to the subsidence, superficial cracks have been observed in two zones: along Paseo de la Reforma and a parallel street, within the clayey zone, and in the northwestern part of the City, in the tuffaceous zone. Those of the first zone have brought about the demolition of several houses and a part of a school and also caused serious damage to the abutments of a recently built bridge. The latter are even more impressive.

The subsidence of the city has also been noticed through the protrusion of well casings. Table 9.8.5 shows a comparison between observed protrusions and measured subsidences in several wells.

It has been shown by correlation studies that for the period 1970 - 1973, approximately 75 per cent of the total subsidence was due to consolidation of the clayey strata and the remaining 25 per cent to the compression of the materials of the deep strata that constitute the aquifer.

There is no doubt about the main cause of Mexico City's subsidence: the overdraft of the aquifer. As a rough estimate the weight of the buildings contribute only 10 to 15 per cent of the total subsidence.

Since 1972 a digital model has been developed to simulate the subsidence of Mexico City. The central idea is to reduce the system of partial differential equations which represent the behavior of the coupled system aquifer-consolidating strata to an integrodifferential equation for the aquifer alone, including the inputs by consolidation through a convolution or memory term (Figueroa Vega, 1973b and 1977).

Some preliminary results show that the simulation is possible, within the limitations imposed by the employed simplifications.

The model is presently in its calibration stage, which has been impaired because data pertaining to the aquifer are relatively scarce (Figueroa Vega, 1977).

9.8.4 ECONOMIC AND SOCIAL IMPACT OF SUBSIDENCE

It is difficult to estimate the economic and social impact of the subsidence of Mexico City. Among the main resulting damages are those to buildings, sidewalks, and pavements, not to mention the continuous dislocation of the freshwater and sewage nets.

On the other hand, the sewage of the city, which originally drained by gravity, has been eliminated by pumping since the flood which occurred during 1951.

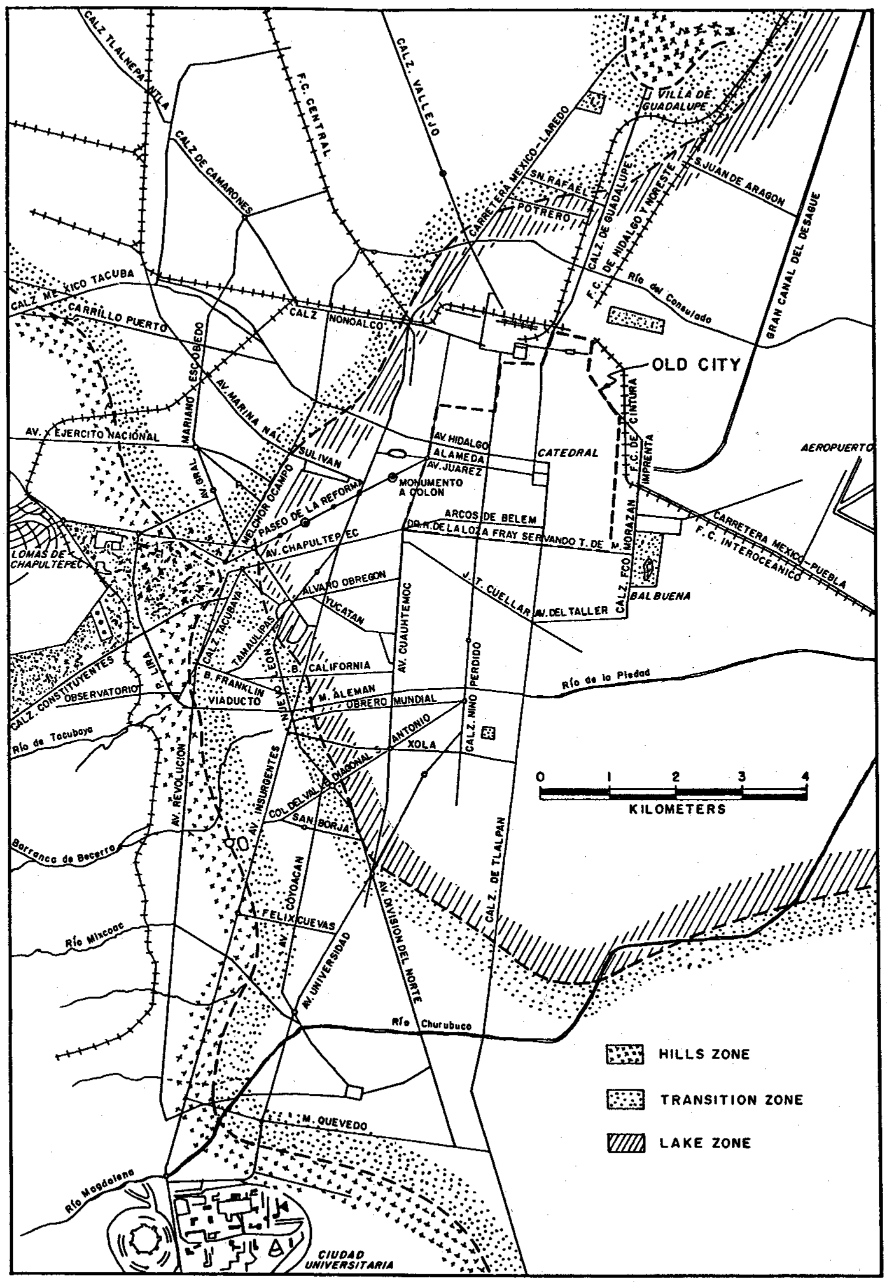

Figure 9.8.7 Zonification of the city (after Marsal and Mazari, 1959).

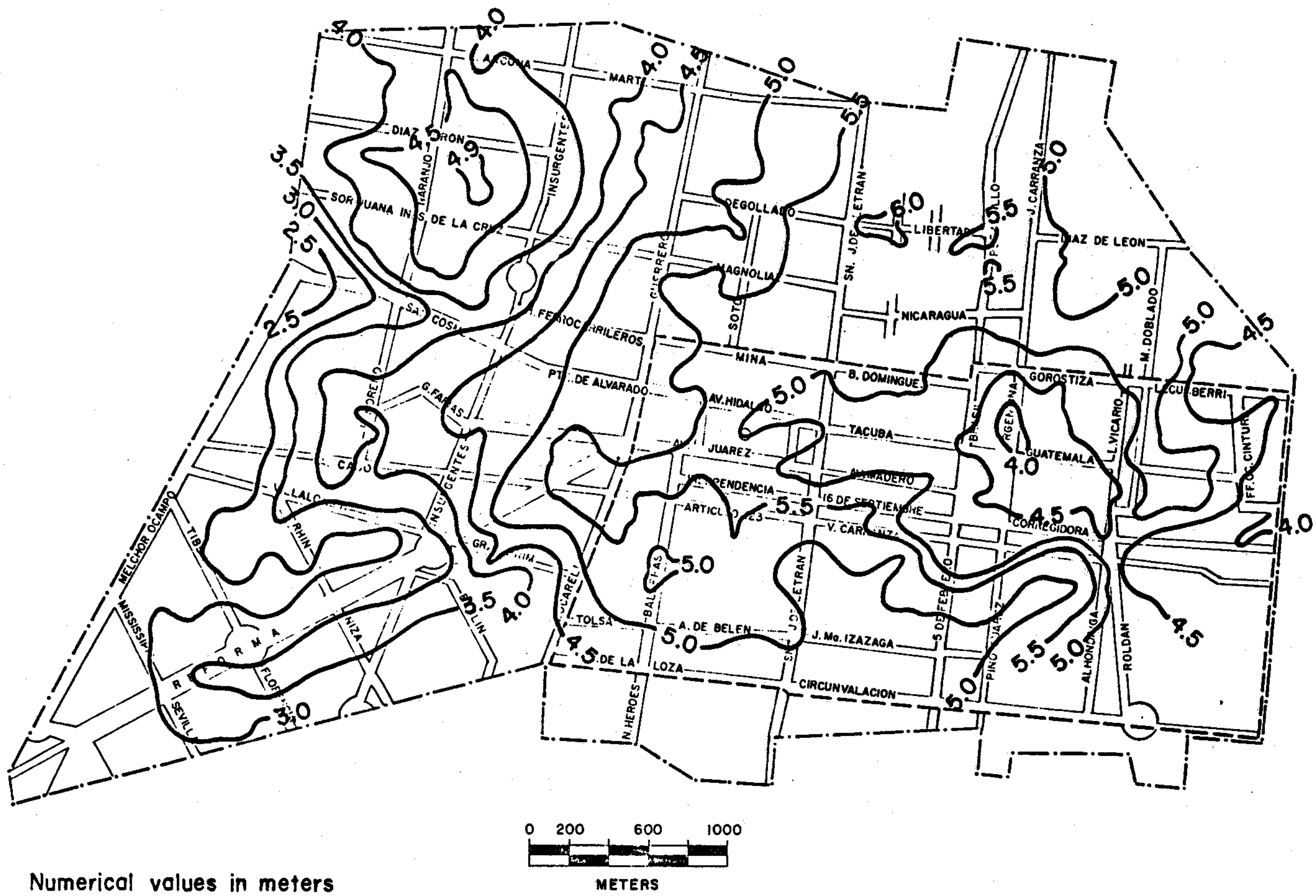

Figure 9.8.8 Subsidence (Old City), 1891-1952 (after Comisión Hidrológica de la Cuenca del Valle de México, 1953).

The constant danger of new floods in case of an electric system, failure, compelled the city authorities to build a Deep Sewage System, with a capacity of 200 m^3/s and a length on the order of 60 km. Complementary collectors are presently under construction.

The total cost of the project would have been much less, if it had been possible to eliminate the sewage by gravity. On the other hand, the overexploitation and the consequent ground-water declines have raised the cost of ground-water extraction, and the loss of water due to dislocation of the distribution net has been estimated up to 15 m^3/s.

Because of above-mentioned factors, the subsidence of Mexico City could conceivably be more expensive than bringing water from other watersheds to avoid the overexploitation of the local aquifer.

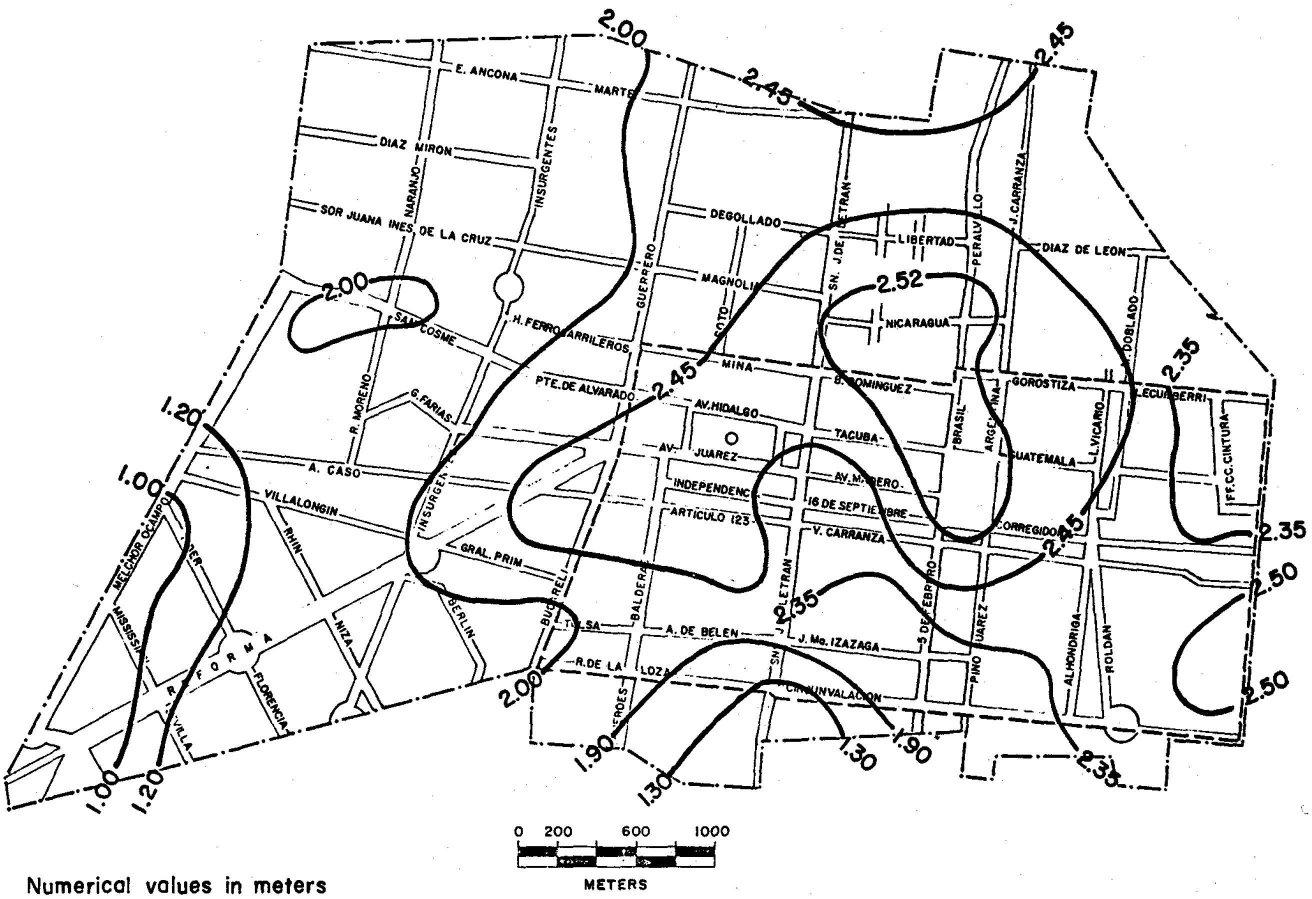

Figure 9.8.9 Subsidence (Old City), 1952-1973 (after Comisión de Aguas del Valle de México, 1975).

9.8.5 LEGAL ASPECTS

From a legal standpoint, the ground water in Mexico belongs to the nation and for this reason no legal action is taken against its overexploitation. As a result, social costs originating from overdraft are normally covered through taxation and water rates.

9.8.6 MEASURES TAKEN TO CONTROL OR AMELIORATE SUBSIDENCE

Soon after the floods of 1951, the City authorities began bringing water from other sources outside the Basin and managed to keep the local extraction constant for many years, as shown in Table 9.8.2. The effect of this may be appreciated in the final portion of the curves of Figure 9.8.12.

The accelerated growth of the city in the last years, which has been an average on the order of 5 per cent annually, has made it necessary to increase slightly the local extractions, as

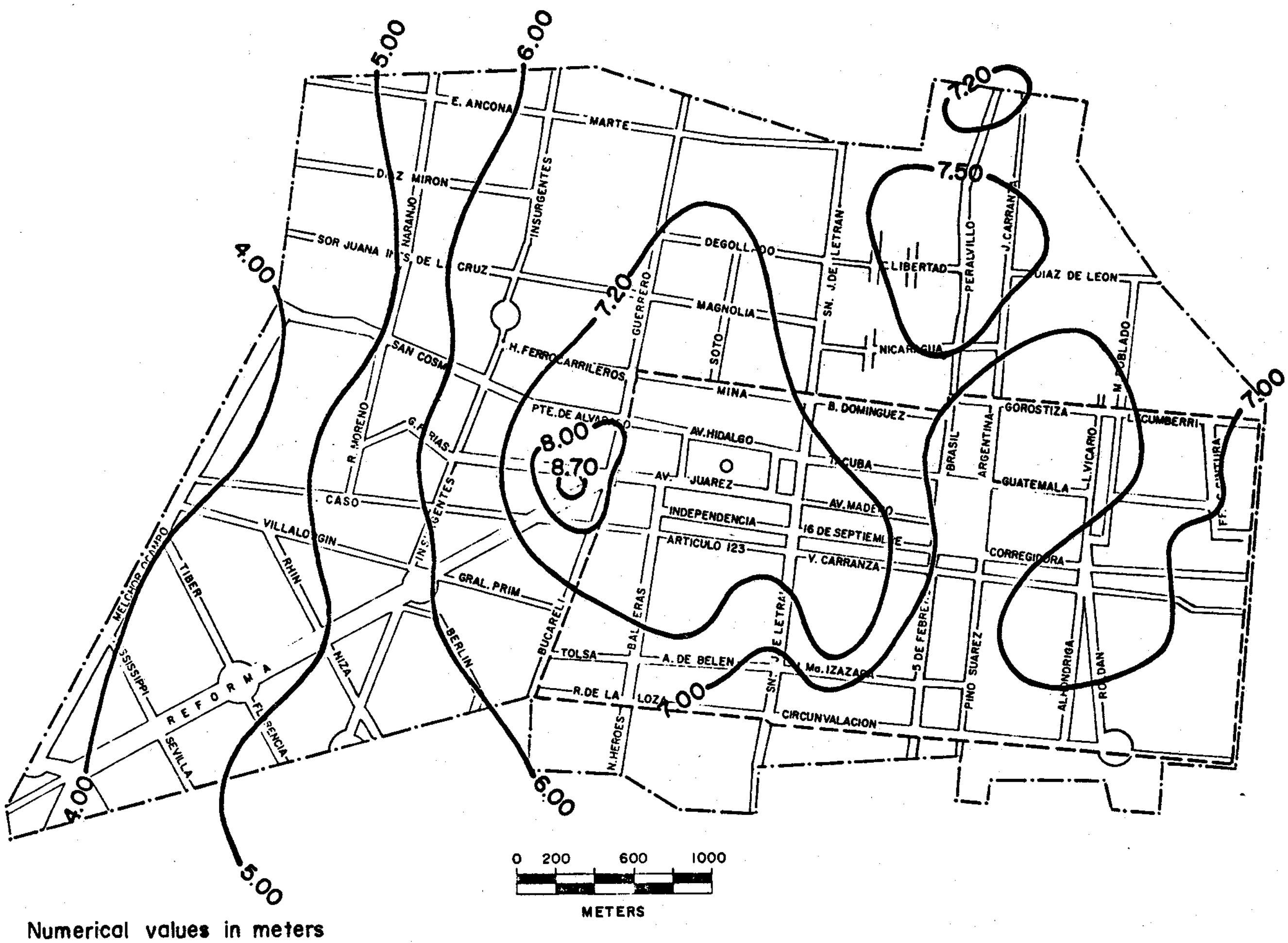

Figure 9.8.10 Subsidence (Old City), 1891-1973 (after Comisión de Aguas del Valle de México, 1975).

shown in the same table. Nevertheless, large projects to bring water from other watersheds are now under way in order to satisfy the future demands and, if possible, to be able to diminish the local extraction in order to solve the subsidence problem. Additionally, the construction of sewage treatment plants for industrial use is now under way and recirculation of water in industries is being made mandatory in order to shut down some of the wells employed by the industries, as these consume almost 30 per cent of the water used by the city. It is estimated that in the near future the substitution of treated sewage water for ground water for industrial use could be of the order of 5 to 7 m^3/s.

The effect of these measures will undoubtedly reduce or cancel the subsidence of the City of Mexico. The schedule for this depends now on political decisions and on availability of funds.

9.8.7 REFERENCES

CARILLO, N. 1948. Influence of artesian wells on the sinking of Mexico City: Proc. of the Int. Conf. on Soil Mechanics, Holland.

COMISION HIDROLOGICA DE LA CUENCA DEL VALLE DE MEXICO. 1953. Boletín de Mecánica de Suelos Num. 1, México, D.F.

___________. 1958. Boletín de Mecinica de Suelos Num. 2, México, D.P.

___________. 1961a. Boletín de Mecánica de Suelos Num. 3, México, D.F.

___________. 1961b. Informe sobre la geologia de la Cuenca del Valle de México y zonas colindantes.

___________. 1963. Hidrologia de la Cuenca del Valle de México, Tomos II y V.

___________. 965. Boletín de Mecánica de Suelos Num. 4, México, D.F.

___________. 1967. Boletín de Mecánica de Suelos Num. 5, México, D.F.

___________. 1970. Boletín de Mecánica de Suelos Num. 6, México, D.F.

COMISION DE AGUAS DEL VALLE DE MEXICO. 1975. Boletín de Mecánica de Suelos Num. 7, Mexico, D.F.

FIGUEROA VEGA, G. E. 1973a. El Hundimiento de la Ciudad de México. Breve Descripción; Recursos Hidráulicos. Vol. II, num. 4; pp. 525-534.

___________. 1973b. Aquifer and subsidence model for Mexico City. 85th annual meeting of The Geological Society of America; v. 5, no. 7, p. 620.

___________. 1977. Subsidence of the City of Mexico, A Historical Review; Publication No. 121 of The International Association of Hydrological Sciences, pp. 35-38.

GAYOL, R. 1925. Estudio de las pertubaciones que en el fondo, de la Ciudad de México ha producido el drenaje de las aquas del subsuelo, por las obras del desaque y rectificación de los errores a que ha dado lugar una incorrecta interpretación de los efectos producidos. Revista Mexicana de Ingeniería y Arquitectura, Vol. III, Num. 2. pp. 96-132.

MARSAL, R. J. 1952. Estudios relativos al comportamiento del subsuelo de la Ciudad de México. Instituto Nacional de Investigacion Cientifical México, D-F,

MARSAL, R. J., HIRIART, F., and SANDOVAL, R. 1951. Hundimiento de la Ciudad de México. Congreso Cientifico Mexicano. México, D.P.

MARSAL, R. J., and MAZARI, M. .1959. El Subsuelo de la Ciudad de México. Primer Congreso Panamericano de Mecánica de Suelos y Cimentaciones, México, D.F. Republished in 1969 with English translation.

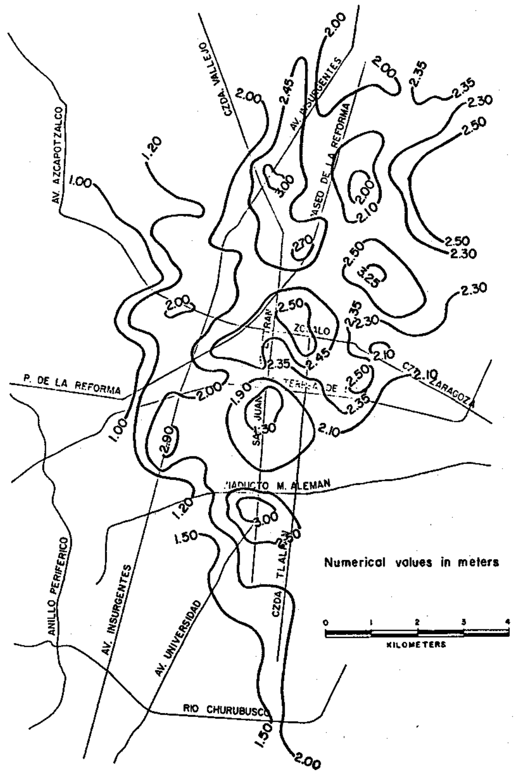

Figure 9.8.11 Subsidence (total area), 1952-1973 (after Comisión de Aguas del Valle de México).

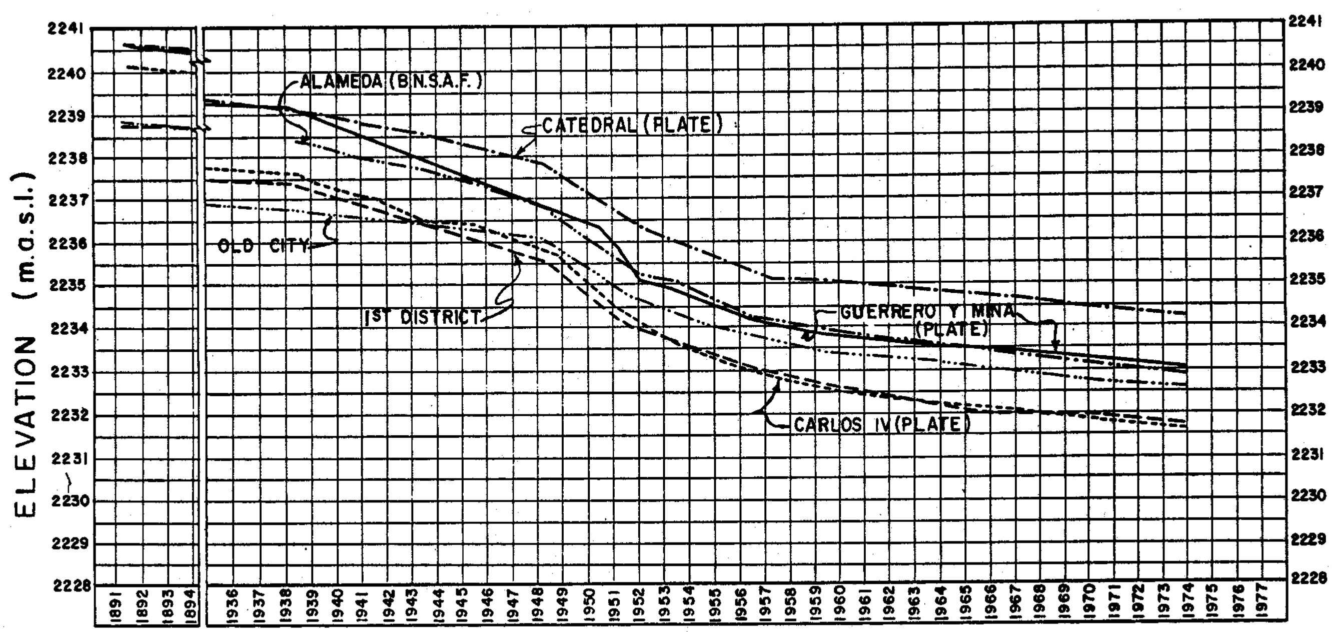

Figure 9.8.12 Subsidence evolution at selected sites (after Comisión de Aguas del Valle de México).

Table 9.8.3 Mexico City subsidence (older part) (from Figueroa Vega, 1977, Table 2).

From - to	Total subsidence (m)	Average (m/year)
1891 - 1938	2.12	0.045
1938 - 1948	0.76	0.076
1948 - 1950	0.88	0.440
1950 - 1951	0.46	0.460
1951 - 1952	0.15	0.150
1952 - 1953	0.26	0.260
1953 - 1957	0.68	0.170
1957 - 1959	0.24	0.120
1959 - 1963	0.22	0.055
1963 - 1966	0.21	0.070
1966 - 1970	0.28	0.070
1970 - 1973	0.17	0.051

Table 9.8.4 Mexico City subsidence (total area) (from Figueroa Vega, 1977, Table 3).

From - to	Total Subsidence (m)	Average (m/year)
1952 - 1959	1.014	0.140
1959 - 1963	0.440	0.110
1963 - 1966	0.254	0.080
1966 - 1970	0.260	0.065
1970 - 1973	0.203	0.059

Table 9.8.5 Well casings protrusion (from Figueroa Vega, 1977, Table 4).

Well	Protrusion 1970 - 1973 (m)	Subsidence 1970 - 1973 (m)
San Juan de Aragón Campamento	0.304	0.440
Czda. Guadalupe	0.130	0.172
Sta. Isabel Tola	0.259	0.320
Monumento de la Revolución Frontón México	0.179	0.200
Jardin de los Angeles No. 2	0.076	0.145
Insurgentes Norte 1407	0.199	0.283
Penitenciaria Jardin	0.233	-
Gómez Farías No. 61	0.113	0.140
Monumento de la Revolución Procuraduría	0.323	-
Jardin de los Angeles No. 3	0.100	0.145
Jardin de los Angeles No. 1	0.146	0.150