Case History No. 9.3. Venice, Italy, by Laura Carbognin, Paolo Gatto, and Giuseppe Mozzi, National Research Council, S. Polo 1364, Venice, Italy; Giuseppe Gambolati, IBM Scientific Center, S. Polo 1364, Venice, Italy; Giuseppe Ricceri, Department of Soil Mechanics, University of Padua, Italy

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9.3.1 INTRODUCTION

Many areas of Italy are affected by land subsidence. Among these, the area of Venice (Figure 9.3.1) has caused the greatest concern. Its sinking in fact, in spite of the relatively small rate, could be fatal, due to the low level of the city in relation to the sea. The well-known floods (or "acque alte," a local idiom meaning high waters), essentially caused by weather and astronomical factors, are indirectly enhanced by subsidence both in amplitude and in frequency. When the studies were started, it became quite clear that, out of the various factors responsible for the sinking, the withdrawal of underground water was the main one. Thus, after a preliminary analysis, the research effort was mainly directed to hydrogeology.

In 1969, the Italian Consiglio Nazionale delle Ricerche (CNR, National Research Council) constituted a working group for the Venice problem. Starting that year an accurate inventory was made of the data already available but widely scattered. They were filed according to

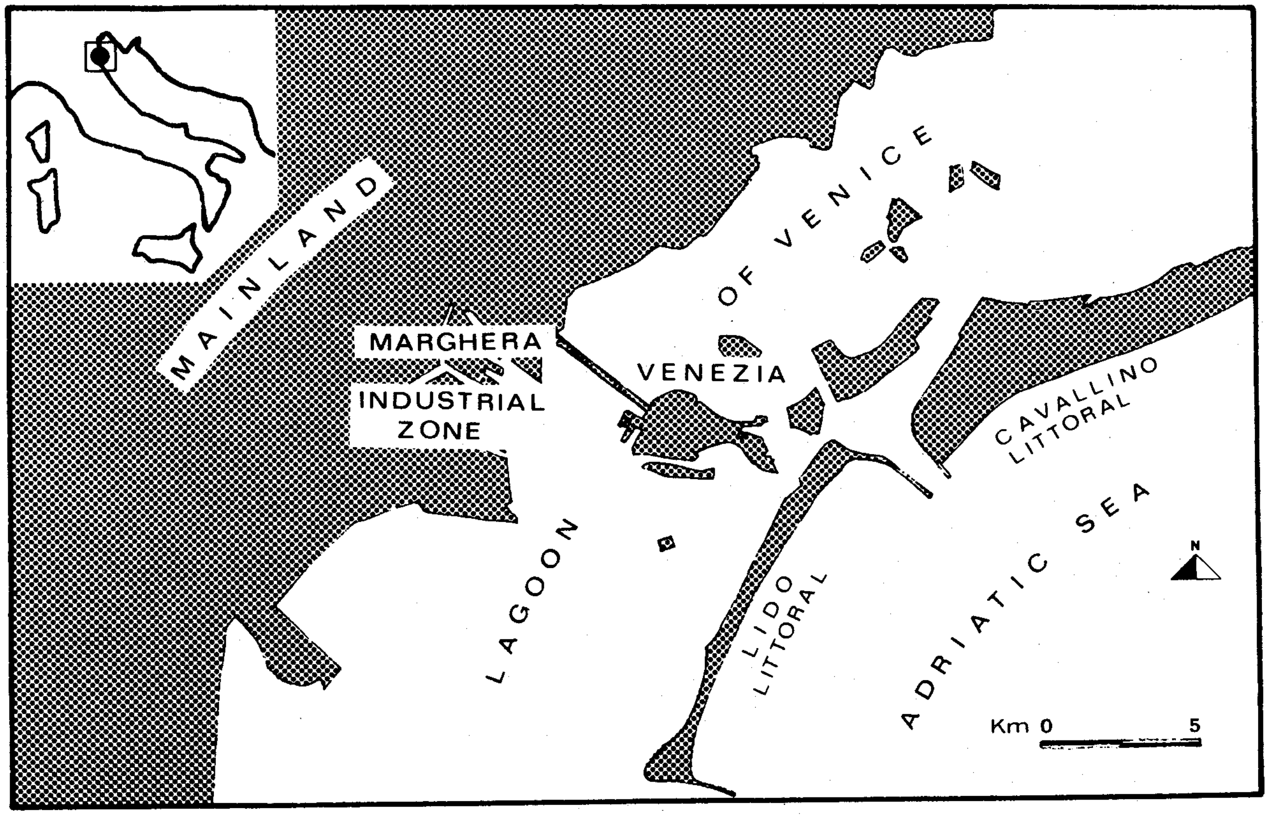

Figure 9.3.1 Map of the Venetian area under investigation.

lithostratigraphy, hydrology, geotechnique, and geodesy. During their processing, specific experimental tests were performed, to validate and supplement the preliminary reconstructions.

The analysis was given two major aims: first, to describe the physical environment where the phenomena under study occur; next, to describe their evolution, to investigate their mechanism, and to make predictions with numerical models. The final results of the research confirm the dependence of the subsidence on the artesian withdrawals, the possibility of stopping the settlement of the city, and even of obtaining a slight rebound by naturally recharging the depleted aquifer system.

9.3.2 THE PHYSICAL ENVIRONMENT

The Venice confined system, down to 1000 m depth (Quarternary basement), is constituted by sand layers (aquifers) bounded by silt and clay layers (aquitards). Moving northwest, towards the foothills of the Alps, the sedimental structure tends to change. Materials are more and more coarse, while the aquitards become thinner, and, at a certain point, they disappear. In the foothill belt the unconsolidated mantle is a whole homogeneous system of sand and gravel. For the hydrologist, it represents the reservoir supplying the aquifer-aquitard system extending beneath Venice and even further.

The Venetian aquifer system has been investigated in detail by taking information from both the existing artesian wells (Alberotanza, et al., 1972) and a new deep test borehole, VE 1 CNR, where continuous samples of the Quarternary series were taken (Consiglio Nazionale Ricerche, 1971). Thousands of analyses were performed on the borehole samples, and a complete physiography of the local subsurface formations was obtained. From this drilling more complete interpretation of the scattered information was made possible. Moreover, the starting point was available for the definition of the hydrogeological stereogram of the region. Figure 9.3.2 is a map of the upper 350 m, where the aquifers are pumped (after Gambolati, et al., 1974, slightly modified). Six aquifers appear, four of which are extensively exploited (2nd, 4th, 5th and 6th).

Permeability, grain-size and clay chemistry of aquifers and aquitards are reported in tables 1, 2 and 3, whose values were obtained by analyzing the cores of the VE 1 CNR and two other test boreholes LIDO 1 and MARGHERA 1.

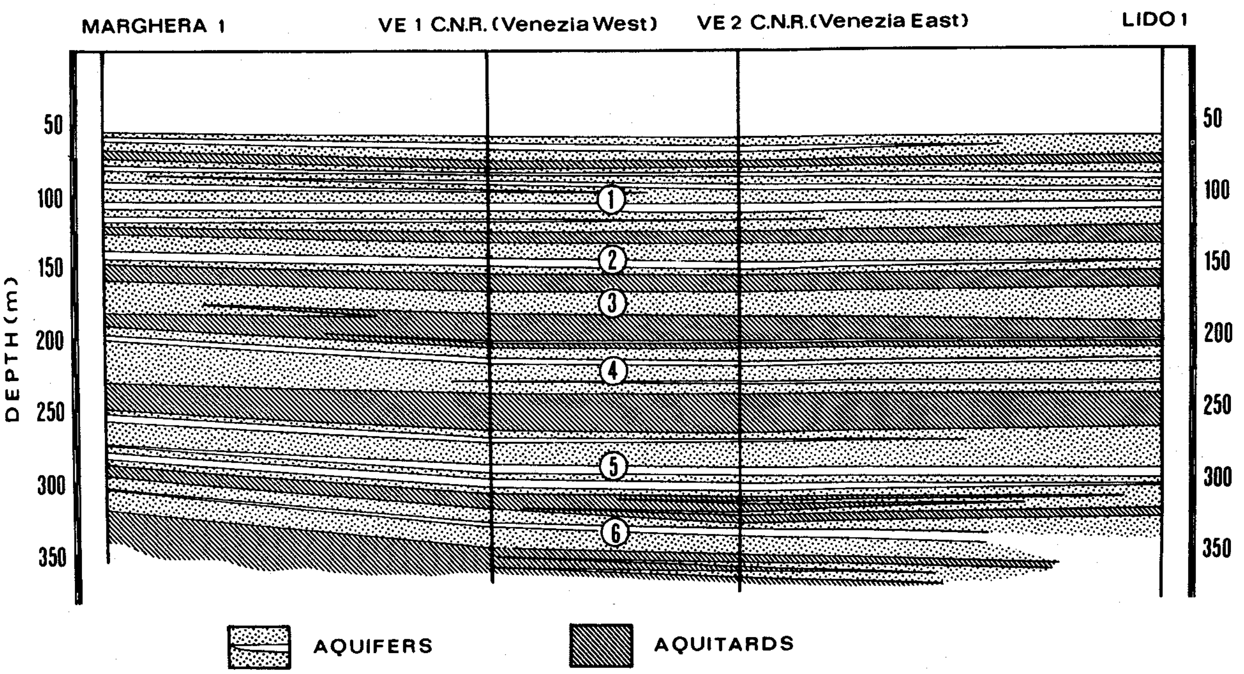

Figure 9.3.2 Hydrogeological map of the confined aquifer system updated using the electric logs recorded in deep test boreholes.

Table 9.3.1 Average permeability of samples taken from VE 1 CNR Borehole (placed in Venice), from laboratory tests.

Depth (metres)	Aquifers (average horizontal permeability)	Aquitards (average vertical permeability)
74- 81		3 x 10^{-5} cm/sec
81-124	1 x 10^{-3} cm/sec	
124-132		7 x 10^{-8} cm/sec
132-153	1 x 10^{-3} cm/sec	
153-163		3 x 10^{-6} cm/sec
163-181	4 x 10^{-5} cm/sec	
181-203		5 x 10^{-7} cm/sec
203-235	6 x 10^{-4} cm/sec	
235-260		6 x 10^{-7} cm/sec
260-302	2 x 10^{-4} cm/sec	
302-318		6 x 10^{-6} cm/sec
318-340	10^{-6} cm/sec[1]	

[1] The 6th aquifer is exploited only at Marghera, since at Venice its permeability is too low.

Table 9.3.2 Summary of grain size analysis as measured in the laboratory on samples taken from the VE 1 CNR borehole (after Gambolati, et al., 1974).

Depth (metres)	Lithotypes			
	Coarse fraction	Sands	Silts	Clays
0- 50	0.3	38.0	41.7	20.0
51-100	0.7	50.0	35.0	14.3
101-150	---	46.2	42.2	11.6
151-200	0.4	33.6	48.2	17.8
201-250	---	26.0	54.0	20.0
251-300	5.6	38.4	34.8	21.2
301-350	---	13.5	61.6	24.9
Average	1.0	35.1	45.4	18.5

Permeability (Table 9.3.1) was defined by laboratory tests performed only on clean sand for aquifers and silt clay for aquitards.

The prevailing fraction (Table 9.3.2) is silt, followed by sand and clay.

The illite is dominant (Table 9.3.3); instead the most plastic one, montmorillonite, is in general rather scarce, and its relative abundancy grows towards the historical center and Lido.

Some details of the mechanical properties of these soils are given here (see a recent and more complete paper by Ricceri and Butterfield, 1974). The values of the compressibility coefficient ($m_V=(\Delta e/\Delta P)(l/l+e_o)$) versus depth (Figure 9.3.3) have been computed by oedometric tests at the actual "in situ" pressure (p_o) in the loading (m_{V1}) and unloading (m_{V2}) curves. The maximum load attained in these tests was $5\div20p_o$ for the samples coming from the upper 100 metres and twice the values of p_o for the others, In Figure 9.3.3, solid lines connect the values m_{V1}, and m_{V2} for each sample; dashed lines refer to oedometric tests where loads were increased slightly above p_o and then gradually reduced to zero. The two coefficients decrease with increasing depth. In particular, m_{V2} seems rather insensitive to the maximum load applied in the test, and its average value is about 20 per cent of M_{V1}.

The reader is referred to the bibliography for further information about the physical aspects of the Venetian formations.

Table 9.3.3 Percentages of various clay-types in the core samples taken from MARGHERA 1, VE 1 CNR, and LIDO 1 test boreholes (after Mozzi et al., 1975).

Clay Minerals	Test boreholes MARGHERA	 VENICE	 LIDO	Average
Illite	48.75	48.45	48.00	48.40
Chlorite	33.75	28.00	30.00	30.58
Kaolinite	11.25	12.80	9.00	11.02
Montmorillonite	6.25	10.75	13.00	10.00

9.3.3 HISTORY OF THE PHENOMENA

By comparing the development of the artesian exploitation and of subsidence, three periods appear distinguishable: the first before 1952, the second from 1952 to 1969 and the last afterwards.

In Figure 9.3.4 the average piezometric level in different places of the Venetian area is plotted versus time.

9.3.3.1 Period before 1952

When the artesian exploitation was not very intensive, subsidence was due only to natural causes; its rate was about one millimetre per year (Leonardi, 1960; Fontes and Bortolami, 1972).

The extraction of the artesian water began about in 1930 when the first factories were established in Marghera. The piezometric level remained above the ground level, except in Venice, where it became lower since the time of World War II. The average decrease was slow all over the area, up to the fifties, when an intensive exploitation started, due to the strong industrial development (Figure 9.3.4).

9.3.3.2 Period between 1952 and 1969

After 1950 the changes became more evident. Artesian water was very actively withdrawn (Serandrei Barbero, 1972) and in the fifties all the hydraulic heads declined below the surface. In the industrial area the average rate reached 0.70 m/y, which is definitely higher than in any other part of the area (Figure 9.3.4). The observed minima were attained in 1969; in Marghera the fourth and fifth aquifers went down to 16 m below surface and in Venice the third and fifth went to 7 m below. From 1952 to 1969, as an average in the industrial zone, a hydraulic head loss of more than 12 m was recorded. In Marghera the withdrawal occurred in about 50 wells, and it was about 460 l/s in 1969; in Venice there were about 10 active wells, but in fact only one (10 l/s) represented the whole extraction of the city. A significant ratio of 1 to 50 existed between the exploitation in the historical center and in Marghera.

In the period 1952-1968 geodetic surveys showed an average subsidence of 6.5 mm/y in the industrial area and 5 mm/y in the city. The most alarming figures appeared between 1968 and 1969, where maxima were observed of more than 17 mm in Marghera and 14 mm in Venice (Caputo et al., 1971) (Figure 5). Overall between 1952 and 1969 the local average subsidence was over 11 cm in the industrial zone and about 9 cm in the city, with local maxima of 14 and 10 cm respectively (Figure 9.3.5)

9.3.3 Years between 1969 and 1975

These years are characterized by a great number of experimental data and theoretical studies worth describing.

After drilling the deep test hole, VE 1 CNR, previously mentioned, two important steps were carried out: the annual repetition of the geodetic survey for controlling the ground movement in the area and the installation of a network of 112 piezometers (24 of which were continuously recording) for controlling the six exploited aquifers (Figure 9.3.6). Therefore it was possible

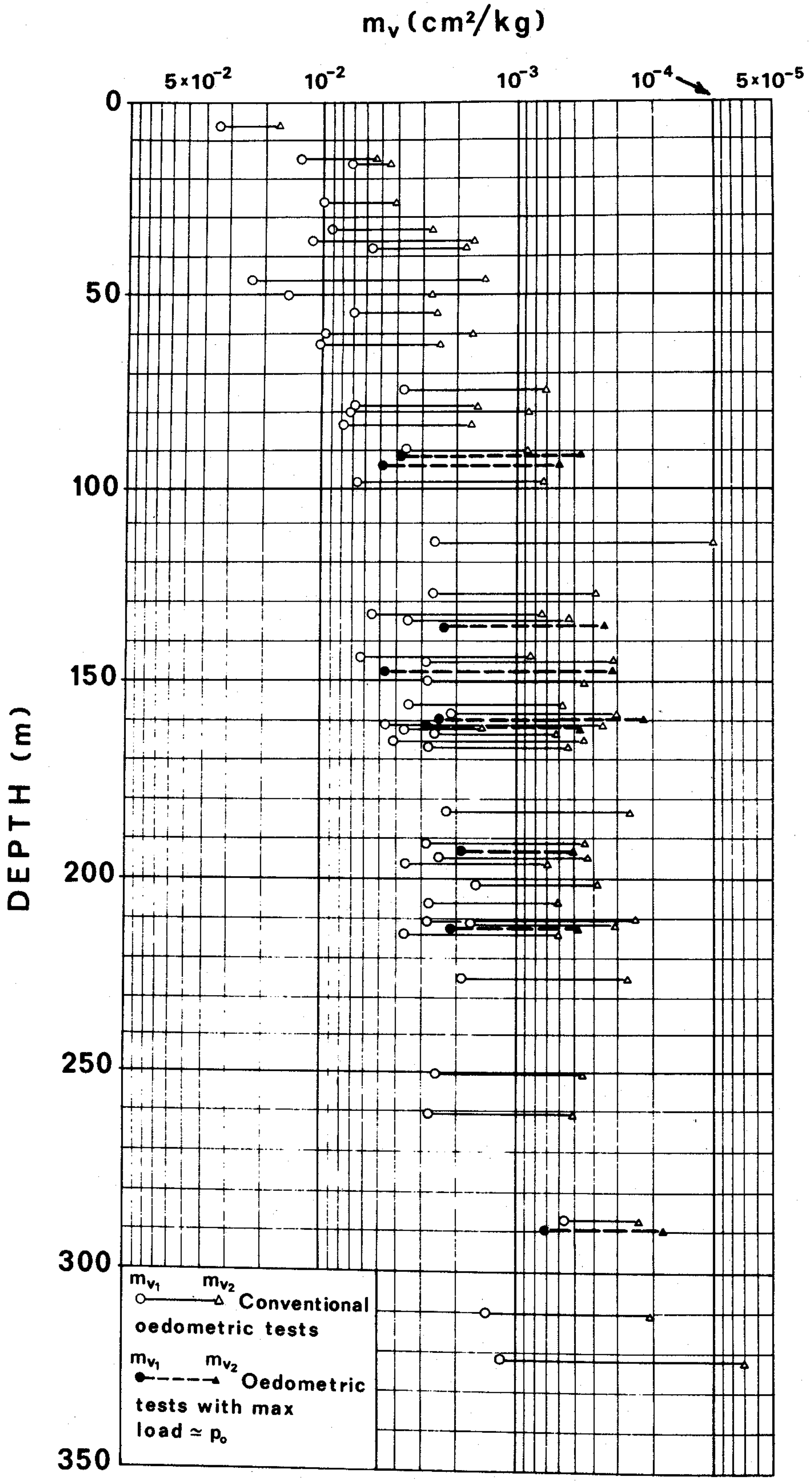

Figure 9.3.3 Coefficients of compressibility m_{v1} and m_{v2} versus depth.

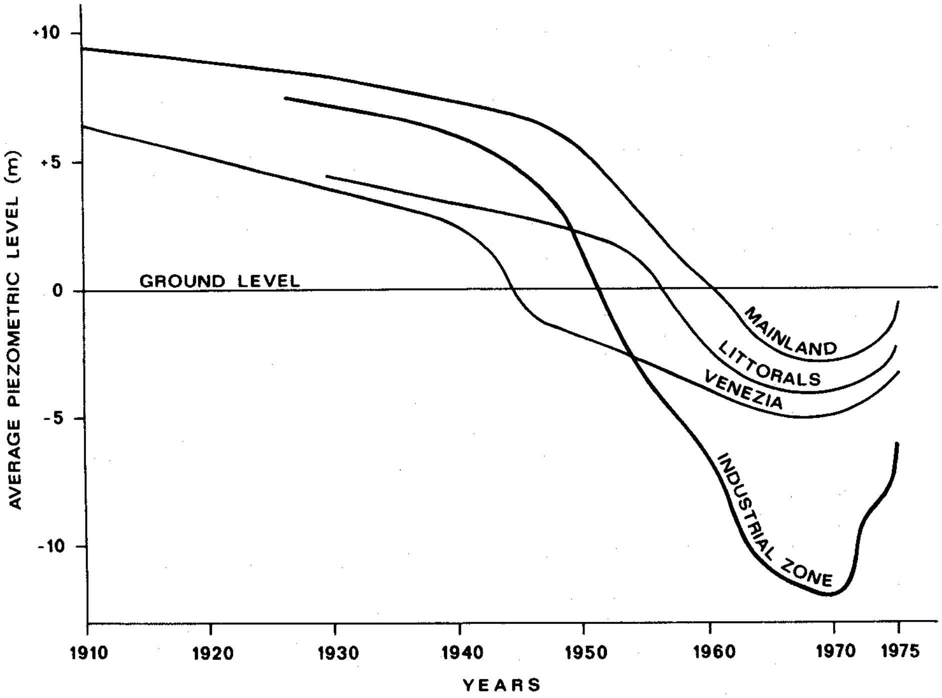

Figure 9.3.4 Average piezometric levels from 1910 to 1975

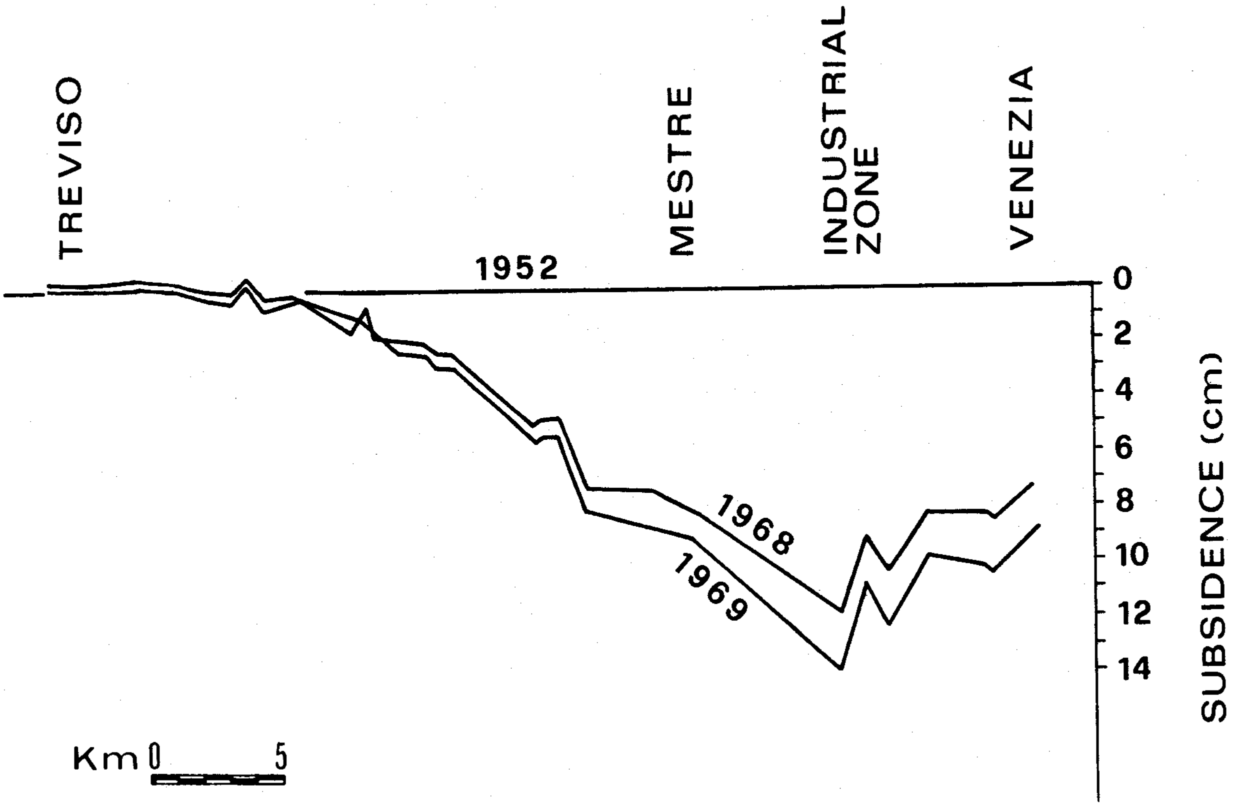

Figure 9.3.5 Comparative plot of the levellings in 1968 and 1969 as referred to 1952

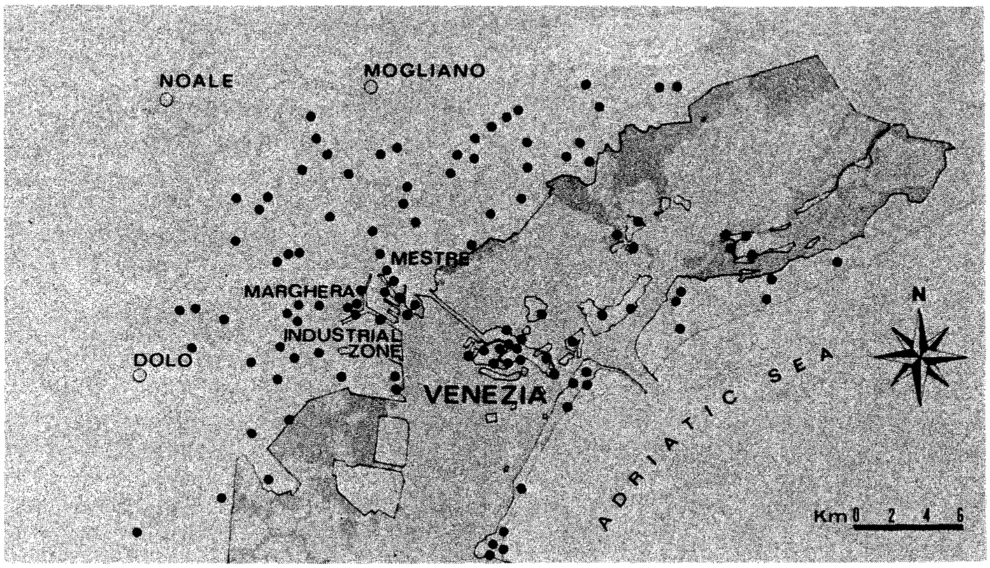

Figure 9.3.6 Map of the 112 piezometers

to annually reconstruct the altimetric profiles and the maps of the equipotential lines (e.g., see Figure 9.3.7 which refers to the 5th aquifer for 1975. Similar behaviour holds true for the previous years).

In general, after the minima recorded in 1969, one can observe a gradual and remarkable, improvement in the piezometric surfaces. In 1975, the average recovery in the industrial area reached a maximum of over 8 m, and in Venice more than 3 m. This new behaviour can be seen in Figure 9.3.4 and it is also well shown in Figure 9.3.8, where the progressive reduction of the depressurized area in recent years is evident.

Similarly to what happened when piezometric levels were declining, a ground-surface rebound is now accompanying the piezometric recovery. After a stability period, which is evident from the 1973 survey (Folloni et al., 1974), the 1975 levelling shows a rebound of the land which, in the historical center, is more than 2 cm with respect to 1969 (Figure 9.3.9). Even taking into account the range of the errors affecting the altimetric curve (Gubellini and DeSanctis Recciardone, 1972), the variation of the ground level in this area remains positive. This is consistent with what appears in the tidal records in Rovinj and Bakar (on the Yugoslavian coast, which is taken to be stable) and those in Venice. Until 1969, the average annual sea level recorded at Venice was apparently increasing with respect to that of the other two stations. In recent years this did not occur any more (Tomasin A., private communication based on official data).

9.3.4 DISCUSSION

9.3.4.1 Analysis of experimental data

We will now analyze the most recent data, i.e., those from the period when the phenomena show a reverse trend.

Looking at the isopiezometric maps, we noted that

1. the piezometric surfaces of the aquifers in the Venetian area show strong depression, assuming the shape of an inverted asymmetrical cone typical of localized pumpage (Mozzi et al., 1975);
2. the maximum drawdown in all the aquifers occurs in the Marghera area, which appears as the main withdrawal center. Minor discrepancies are seen in the islands of Murano, Burano, Le Vignole and Lido:
3. the greatest depressurization is found in the 4th and 5th aquifers;

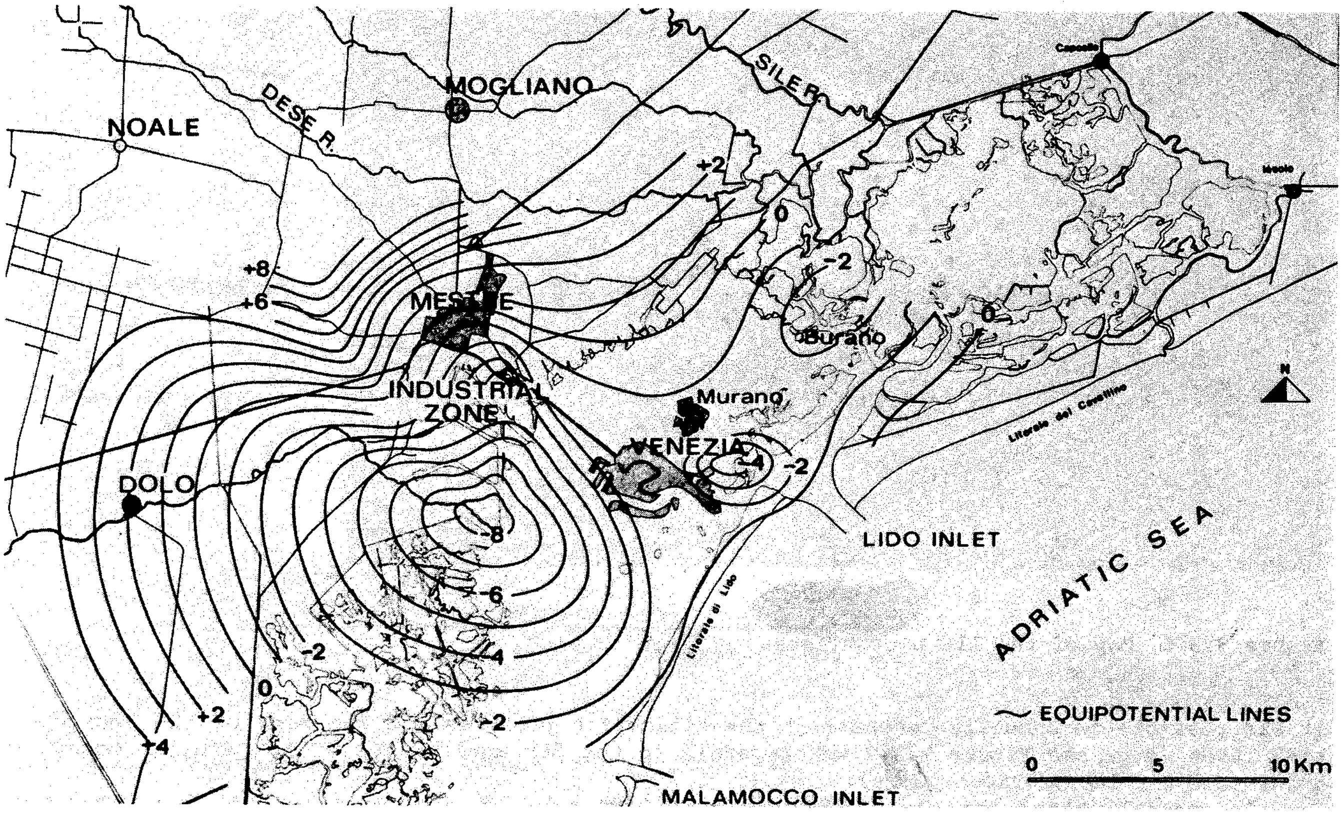

Figure 9.3.7 Piezometric surface of the 5th aquifer in 1975. Equipotential lines are given in metres a.s.l.

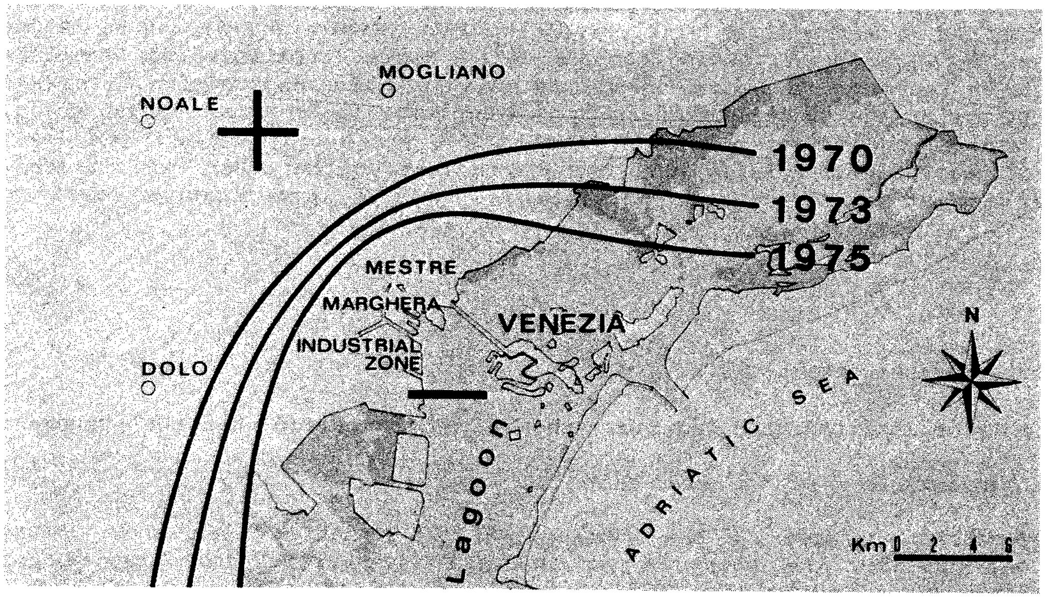

Figure 9.3.8 Boundary of the areas where average piezometric level is above (+) or below (-) the ground level in 1970, 1973 and 1975.

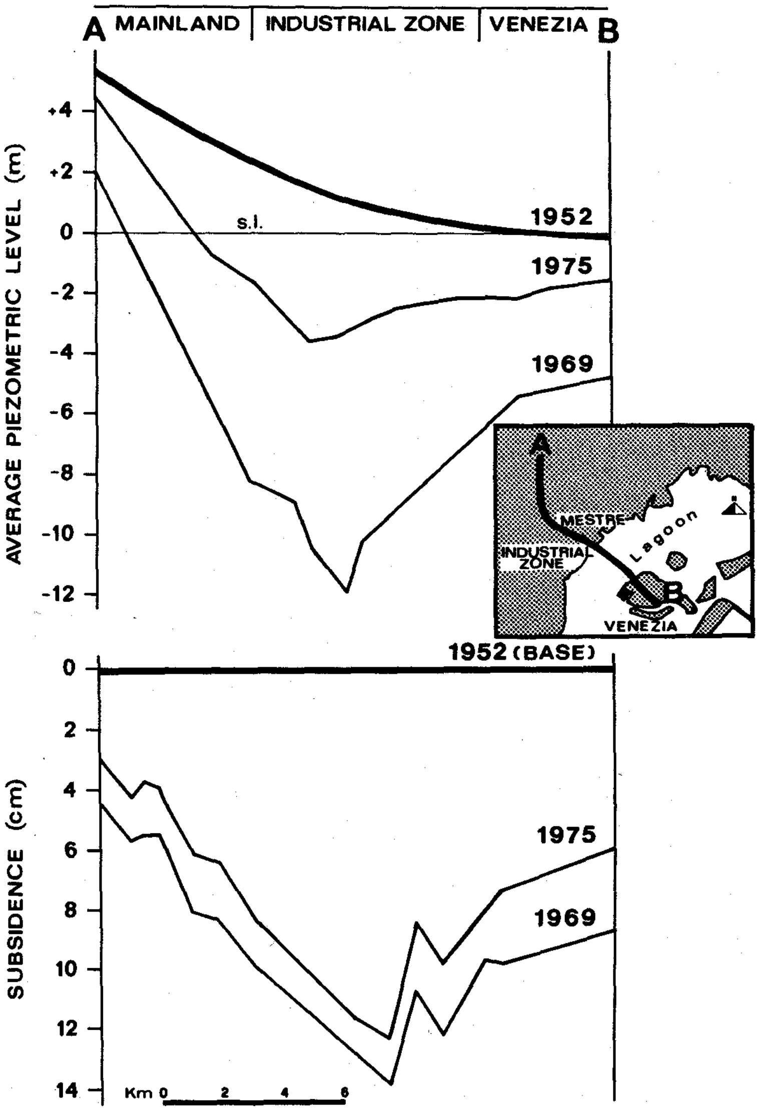

Figure 9.3.9 Comparison of the average piezometric levels and ground levels over mainland (A) and Venice (B).

4. the development of the equipotential lines shows that pumpage at Marghera affects the natural hydraulic balance of the aquifers also in the historical center, where the local withdrawals do not account for the observed drawdown;
5. the distance between equipotential lines gets smaller landward. Figure 9.3.7 also suggests that a no-flux boundary condition exists seaward. This is in keeping with the reconstructed geology.

The aquifer recovery is due to a decrease in the water exploitation. Since 1970, some areas in the district have been supplied by the public aqueduct. The industrial activity of Marghera has been reduced. Above all, well drilling was prohibited in the Venetian plain. In January 1975, the new industrial aqueduct, supplied by the Sile River, was put into operation (a 60 per cent reduction in the number of active wells was observed in Marghera from 1969 to 1975, when the withdrawal was estimated to be about 200 l/s).

The raising of the hydraulic levels is certainly not due to the increased recharge of the aquifers, since in the last decade the natural water supply in the recharge area is diminishing (Carbognin et al., in press).

The levellings, as already stated, show the cessation of the subsidence and a certain rebound. The close connection between withdrawal and subsidence is evident in Figure 9.3.9, where the altimetrical variations and the average piezometric level variations are given for the periods 1952-69 and 1969-75, along the same section from the mainland to Venice. Graphical comparison visualizes the presence of minima in the industrial zone, and similar behaviour of the processes during exploitation and recovery. In the rebound phase, however, we notice that while at Marghera a strong recovery determines a slight altimetrical rebound, at Venice a minor piezometric recovery causes a greater rebound. This can be ascribed to the diverse nature of the cohesive soils at Marghera and Venice.

The assumption of the interdependence between the piezometric and the altimetric variations was statistically verified. In fact, the linear correlation coefficient, with a 95 per cent probability, is between 0.70 and 0.92. The connection between the two variables is therefore expected to be extremely high. Consequently, the coefficient of determination indicates that the piezometric variations account for 70 per cent of the altimetric ones, in terms of variance and in the limiting hypothesis of linear behaviour. The residual variance must be explained by other factors, such as natural subsidence and loading by buildings, but also errors in measurements and deviation from the linear hypothesis.

The interpretation of the subsidence to piezometric variations ratio ($R = \eta/\Delta h$) is also interesting. Its trend in the years 1952-69 (Figure 9.3.10-A) is progressively rising from the industrial zone (1/109) towards the historical center (1/54). This variation can be attributed to the already noted gradual increase towards Venice of the more compressible soils. It explains why in Venice, where less water was pumped than in Marghera, a subsidence of the same magnitude was observed. A similar behaviour is found in the rebound phase (Figure 9.3.10-B) between 1969 and 1975. However in this period, the curve lies definitely below the other one, thus confirming that the elasticity of the system is very limited.

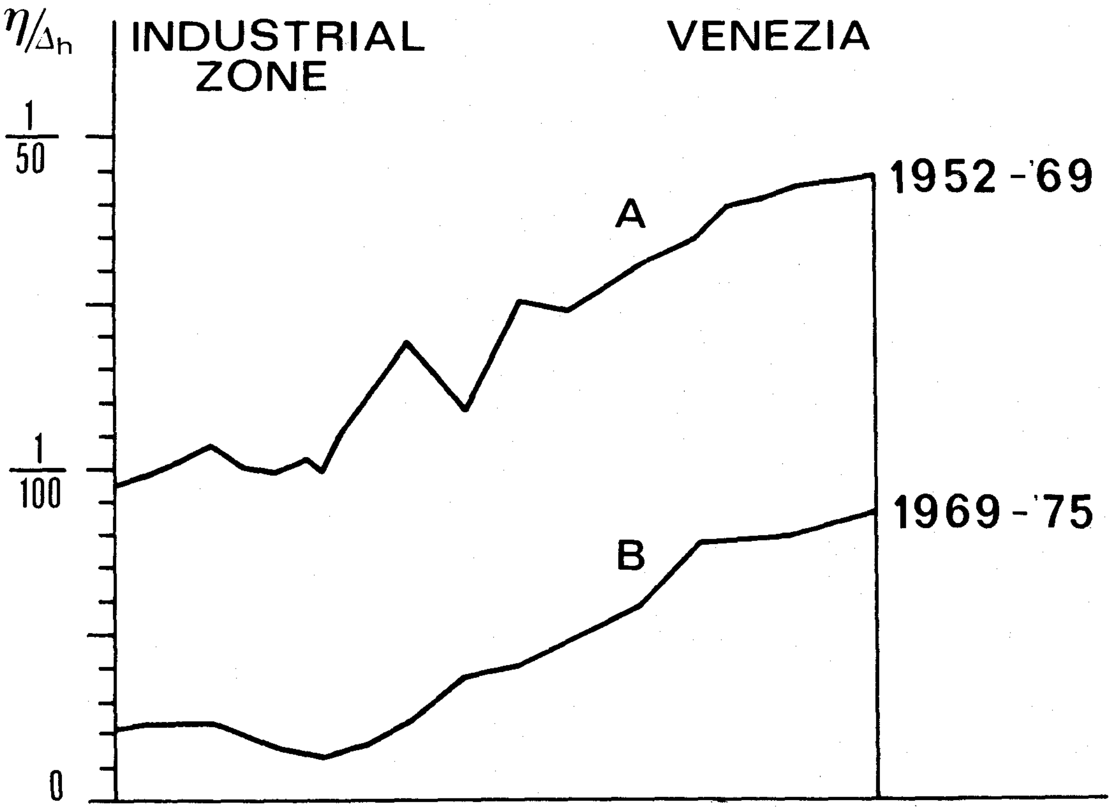

Figure 9.3.10 The ratio of subsidence to piezometric variations from the industrial zone to Venice; A, settlement and B, rebound.

9.3.4.2 Predictive simulations with the new records

Recently, a numerical model based on the classical diffusion equation and one-dimensional vertical consolidation has been used to simulate the past behaviour of the Venice subsidence and to predict the future settlement of the city (Gambolati and Freeze, 1973; Gambolati et al, 1974; Gambolati et al., 1975). A complete description of the approach together with an extensive discussion of the underlying assumptions may be found in the works cited.

The model has been applied again by using the new records to check its ability to reproduce the complex event at hand and to verify "a posteriori" its predictive capacity.

To date the pumpage at Marghera has been reduced to 40 per cent of its maximum value (460 l/s in 1969) and this change in the withdrawal rate has been assumed to have occurred in 1970, for it is apparent from Figure 9.3.4 that the flow field recovery in Marghera started in 1970. Permeability distribution is the same as that used in the previous simulation (Gambolati et al., 1974) while the soil compressibility in rebound has been increased to 20 per cent of the corresponding values in compression, as is evidenced by the most recent laboratory tests summarized in Figure 9.3.3. Therefore, the new results are slightly different from the early predictions given in figures 21 and 22 of the paper by Gambolati et al., 1974.

Figure 9.3.11 and Figure 9.3.12 show the piezometric decline in the first aquifer (where the largest amount of data is available) and the Venice subsidence respectively versus time as provided by the mathematical model using the updated records. For the benefit of the reader the behaviour during the calibration period has been reported as well. The comparison with the experimental observations indicate a fairly good agreement, and especially so, if one considers the degree of uncertainty which is inevitably related to physical events of such a great complexity. This is further evidence of the adequacy of the above model to reliably predict the settlement of Venice. At the same time the results allow the conclusion that the numerical models can be useful tools to investigate and keep under control land subsidence caused by subsurface fluid removal.

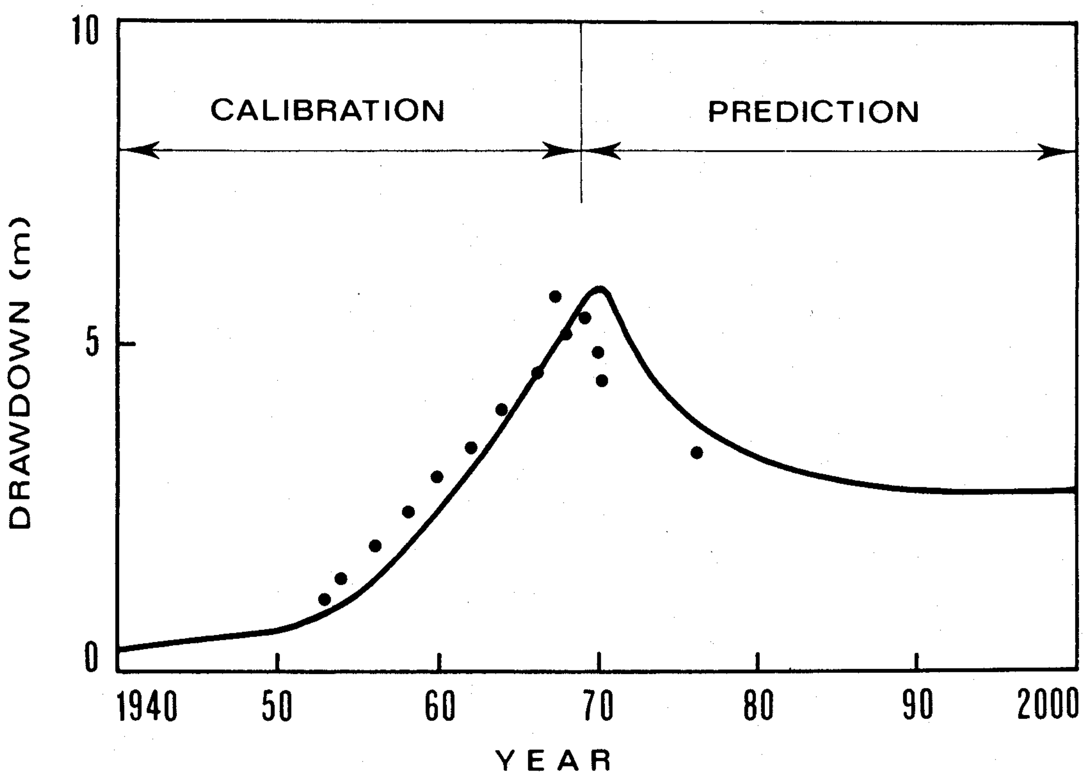

Figure 9.3.11 Piezometric decline versus time in the first aquifer. The closed circles represent experimental records and the solid line gives the response of the model using the new data in our possession.

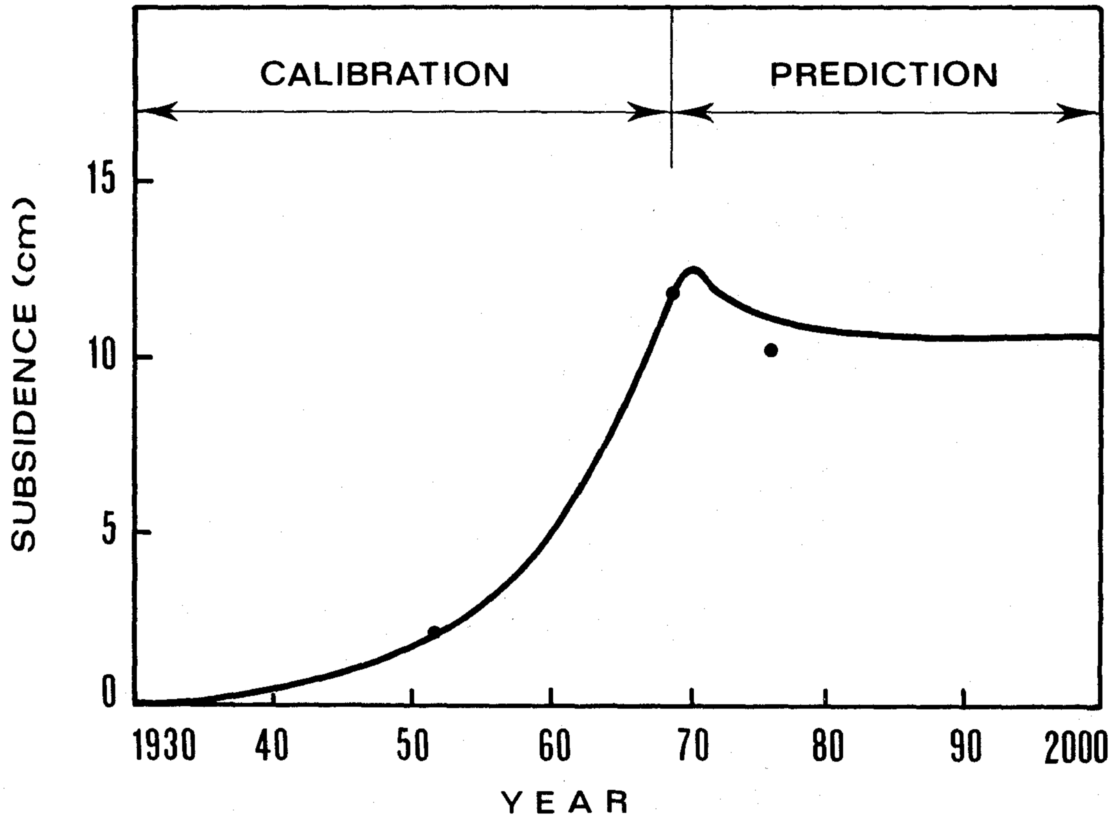

Figure 9.3.12 Subsidence in Venice versus time as provided by the model using the new data in our possession. The experimental records (o) are indicated.

9.3.5 CONCLUSIONS

The results of the experimental research have confirmed that also in the case of Venice, the sinking was caused by the artesian withdrawals. Also statistical analysis attributes 70 per cent of land subsidence occurring between 1952-1969 to the withdrawal of the underground water.

The experimental data showed that the pumpage performed at Marghera has greatly altered the natural flow field under the historical center and that the effects of the resulting subsidence are not uniformly distributed. In fact, for every metre of piezometric decline, the subsidence in the industrial area and in Venice was respectively 1 and 2 centimetres. This is connected to the relative increment towards Venice of the clay-type soils, which are more compressible, making the level of the city more dependent on the piezometric situation.

Soil deformations related to hydraulic head variations occur in a relatively short time due to the fact that aquitards are mainly silty and each of them is interrupted by thin sandy layers which facilitate the drainage.

But the most significant fact that arises from our investigation remains in any case the sudden rise of the piezometric levels recorded in the whole area since 1970, and related to a significant reduction of the artesian withdrawals in the last years. It is also important that there is a parallel surface rebound (2 cm in Venice), that ensures that land subsidence has been arrested. This result is in agreement with the predictions from the mathematical model.

Since a more careful use of the underground waters gives a very quick recovery, one can trust that a complete re-establishment of the natural hydraulic balance can be obtained, maybe with further intervention against wasting water (which can be estimated to be about 4.5 m^3/s due to the spontaneous spilling in the adjacent areas which influence the Venetian aquifer system).

Recovery will not, however, bring back the land to the original position, as it has been demonstrated that the reversibility of the compaction of the aquitards is possible for only 20 per cent (which would correspond to a rebound of about 3 cm).

Although the drawdown of the piezometric levels due to the intensive extractions of 1952-69 was the principal cause of the subsidence, we do not see a need for stopping the residual extractions.

Because of the unstable situation of Venice, it is necessary to continue the control of the piezometric levels of the aquifers and the ground altimetry. This is the only system by which we can evidence possible future variations from the present trend.

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Note by the authors:

After 1975, both piezometric and geodetic surveys were continued on the studied area. The 1978 situation shows that the natural repressuring of the aquifers has continued and today artesian heads are coming back to the value recorded before the over-pumpage in 1952. At the same time precise leveling shows that the land has stabilized after the 1975 rebound.