Case History No. 9.15. Ravenna, Italy, by Laura Carbognin, Paolo Gatto, and Giuseppe Mozzi, National Research Council, S. Polo 1364, Venice, Italy

9.15.1 INTRODUCTION

Ravenna is about 60 km south of the Po delta, in a symmetric position with respect to Venice (Figure 9.15.1). Land subsidence in this area has been observed for a long time but only recently did the related consequences become critical. Progressively affecting the entire territory of about 700 km^2 (Figure 9.15.2), the subsidence increasingly threatens not only the industrial area, and the urban zones, but also the surrounding vast marshland reclamations which could be submerged once again. The existence of several buildings and historical monuments is jeopardized as well, since their foundations have to be kept dry by pumping out water continuously.

It became clear from the first analysis, started in 1970 by the National Research Council of Venice at the request of the Municipality of Ravenna, that the causes of land subsidence had to be mainly ascribed to the removal of fluids from the subsurface (Bertoni, et al., 1973).

The investigation began with the inventory of available stratigraphic, hydrological, geotechnical, and geodetic data. Unfortunately no information was available concerning physical and mechanical properties of the formations. Good historical data are available for both piezometry of the aquifers and subsidence. Field measurements such as leveling and hydraulic head records were carried out almost annually, using networks of suitably placed bench marks and piezometers, similarly to what was done for Venice. The preliminary hydrogeological in-

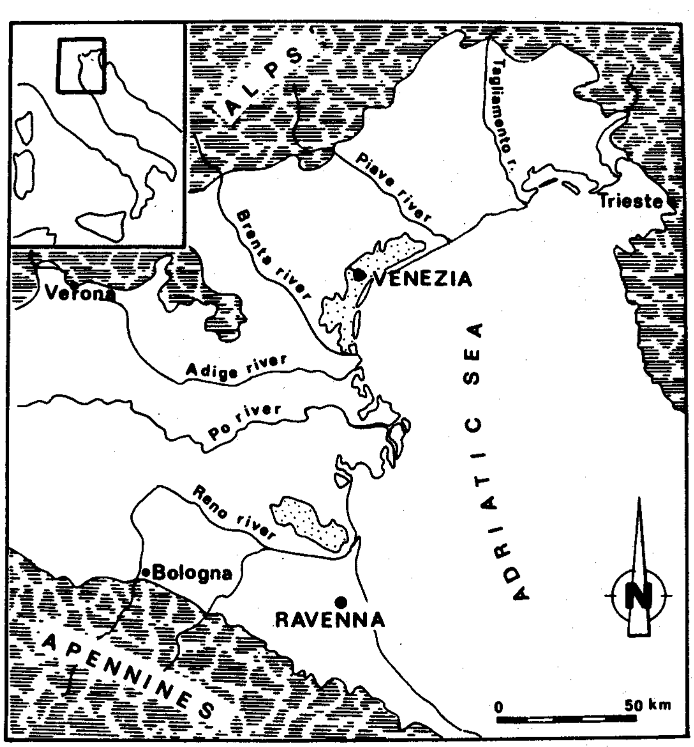

Figure 9.15.1 Areas of Ravenna and Venezia. They are symmetric with respect to the Po delta. (From Carbognin, et al., 1978, Figure 13; published with permission of the American Society of Civil Engineers.)

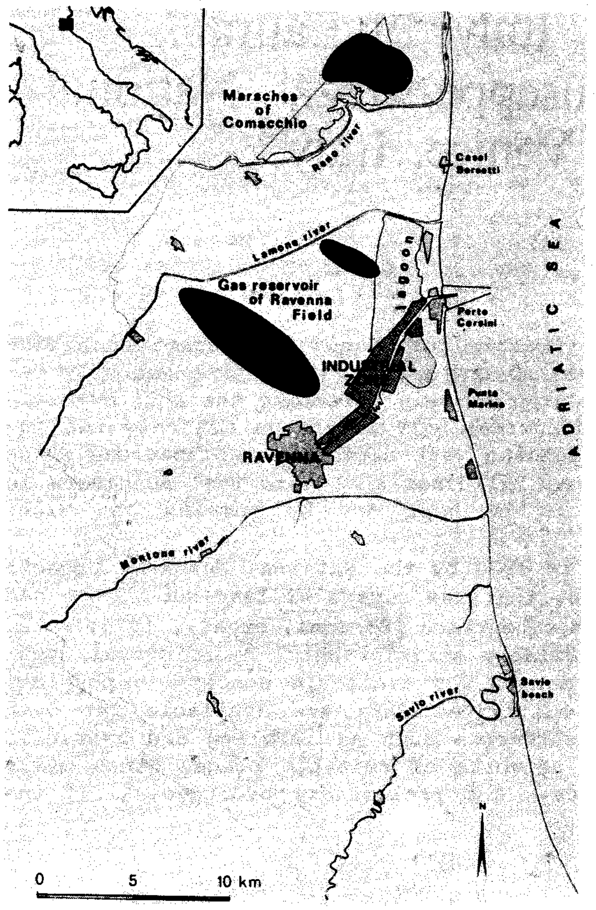

Figure 9.15.2 Map of the area under investigation (District of Ravenna). (From Carbognin, et al., 1978, Figure 1; published with permission of the American Society of Civil Engineers.)

vestigation will be further improved by using the information obtained through specifically programmed test holes. The research already undertaken has, however, provided a good understanding of the overall subsidence occurrence.

After a preliminary description of the geological environment, this paper presents the history of the pressure decline in the aquifer and land settlement and discusses their relationships.

9.15.2 HYDROLOGICAL FEATURES

The total thickness of Quaternary sediments in the Ravenna area ranges between 1500 and 3000 metres and mostly consists of sandy and silty-clay layers of alluvial and marine origin. The bottom of the Quaternary sediments follows the structure of the pre-Quaternary substratum, characterized by folds and faulted overfolds which are parallel to the main tectonic profiles of the Apennines and include several gas-bearing traps at depths on the order of 2000 m (Figure 9.15.3) (Agip Mineraria, 1969a).

The presence of massive Quaternary deposits confirms that in the past the geologic subsidence was quite pronounced in this area and is still rather active (Salvioni, 1957); it is apparent that the tectonic stresses acting along a SW direction tend to increase the Po basin curvature. The deep structure has influenced the thickness of the Neozoic formations and consequently the subsidence rate exhibits a non-uniform space distribution (Dal Piaz, 1969).

The stratigraphy of the upper Quaternary sediments is not defined with accuracy, due to the partial lack of information. However, it has been possible to reconstruct schematically the map

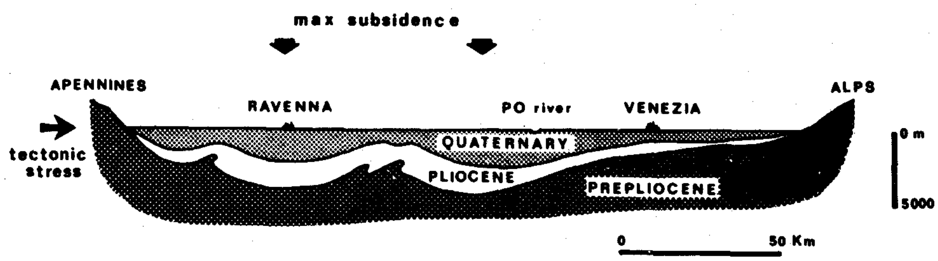

Figure 9.15.3 Very schematic cross-section of the Po Valley between Venezia and Ravenna (Agip Mineraria, 1969a).

of the aquifer system down to 500 m using the relative positions of the intakes of several pumping wells and other sparse lithological information.

Between 90 and 430 m the confined units are well identified and rather continuous (Figure 9.15.4) (Bertoni, et al., 1973). In the upper 90 m the areal continuity of the sands is quite limited and the definition of large important formations is uncertain. This portion of the system is little exploited due both to reduced productivity and possible water pollution from the overlying polluted unconfined aquifer. Below 430 m the salt content becomes very high (Agip Mineraria, 1972) and the water cannot be used any longer for industrial and/or agricultural purposes.

From the information available, the aquitards separating the various sandy formations appear to be rather continuous with very low permeability. The logs suggest that large amounts of silty sediments are present. The aquifers shown in Figure 9.15.4 consist mostly of fine and medium sands with occasional shells. However, clayey or silty sands also may be found which locally reduce the aquifer transmissivity.

The recharge of this confined multi-aquifer system comes mainly from the foothills of the Apennines as well as from the Po River basin (Figure 9.15.5) (Carbognin, et al., 1978). It is clearly impossible on the basis of the available records to quantify the respective contributions.

9.15.3 SUBSOIL RESOURCES EXPLOITATION AND SUBSIDENCE

It was soon quite clear that as in the Venice case the surface settlement was caused by the removal of subsoil fluids. Since the withdrawal rate is hard to assess with accuracy, the behaviour of the subsurface flow field was kept under periodic observation through a network of 120 piezometers (Figure 9.15.6). A 1972 survey of the area revealed that 877 active wells tapped the 9 confined aquifers. These wells were scattered across the area, but the most recent and productive ones were concentrated on the industrial zone (Bertoni, et al., 1973).

Figure 9.15.7 shows the behavior of the piezometric levels of the various aquifers underlying the historical center (Carbognin, et al., 1978). It is evident from this figure that:

- -- there was a lowering of the hydraulic head below the ground level beginning in the 1950's;
- -- the greatest decline occurred after 1960, simultaneously with the development of the nearby industrial zone;
- -- aquifers 4 and 5 are the most intensively exploited;
- -- among the head gradients found in the aquitards the highest occurs between aquifers 3 and 4, with a difference of head of 22.50 m;
- -- in recent years the piezometric level tends to be constant;
- -- aquifers exhibit a somewhat independent hydraulic behavior (except perhaps aquifers 1 and 2). This is further evidence that the basin underlying Ravenna is a real multi-aquifer system.

Piezometric records permitted periodical plotting of equipotential lines. As an example, Figure 9.15.8 gives the piezometric surface in 1977 averaged over all the aquifers between 100 and 430 m (Carbognin, et al., 1978). It may be observed that the maximum drawdown of about 40 m occurs in the industrial zone (it was the same in 1972). Today, however, a large decline extends even

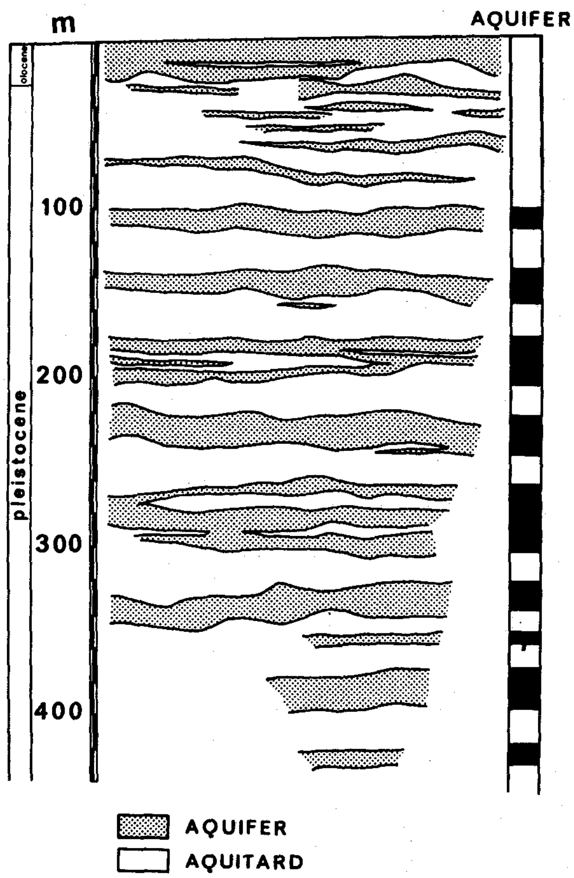

Figure 9.15.4 Schematic cross-section of the Ravenna aquifer system. (From Carbognin, et al., 1978, Figure 3; published with permission of the American Society of Civil Engineers.)

to the western and southern parts of the territory due to the increase of water withdrawn for agricultural uses, seaside resorts, and new industrial parks springing up on the outskirts of Ravenna.

The asymmetric cone of depression develops with its major axis from NW to SE, greatly affecting the coastline. A strong gradient appears in the southern part, corresponding to the direction of the Apennines recharge.

Between 1972 and 1977, the maximum decline of the piezometric head has not changed substantially (see Figure 9.15.7). Nevertheless, even if encouraging, this does not correspond to the arresting of land subsidence, as will be seen later.

So far as the geodetic survey of the area is concerned, it was not homogeneous in time. Although the land subsidence began in the early 1950's, only since 1970 have land levelings been systematically carried out at the same time as the measurement of the piezometric levels. As an example, Figure 9.15.9 shows the subsidence experienced from 1972 to 1977. The general increase of the subsidence in these years is shown by the two maps of Figure 9.15.10. In the evaluation of the rate of subsidence linear trends are assumed. It may be noted that the area experiencing subsidence exceeding 3 cm/y in the latter period is about 30 times greater than the corresponding area in the former one. Moreover, a settlement rate exceeding 5 cm/y was experienced in the last few years (Figure 9.15.10b). The maximum rate of about 11 cm was recorded in the industrial zone between 1972 and 1973 and in Ravenna's historical center about 8 cm was observed.

The shape of the subsiding areas is in close correspondence with the cone of depression of the aquifers in both periods. The time and space correlation between ground sinking and water withdrawals is clearly evidenced in Figure 9.15.11, which shows the average piezometric level and subsidence from 1950 to 1977 along a line crossing the city and extending to the country

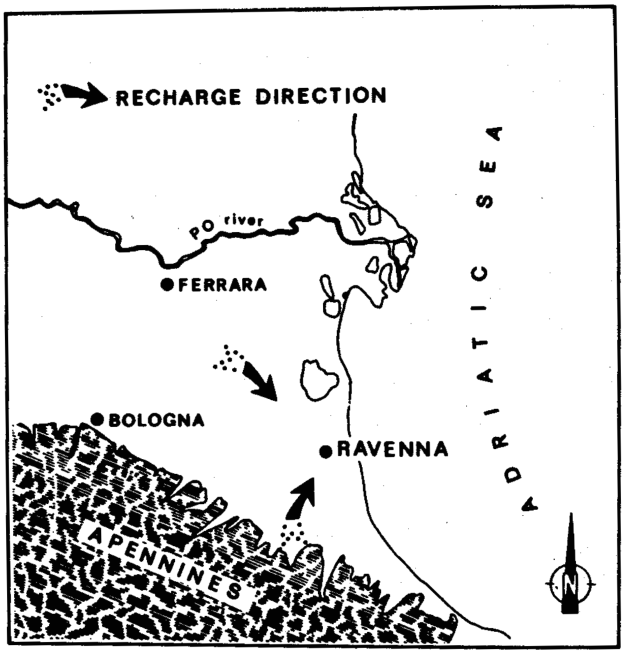

Figure 9.15.5 Map of the recharge areas of the Ravenna aquifer system. (From Carbognin, et al., 1978, Figure 4; published with permission of the American Society of Civil Engineers.)

side. This comparison stresses the nearly absolute behavioral identity of these parameters (Carbognin, et al., 1978).

From 1949 to 1977 maximum subsidence of about 1.20 m was recorded in the industrial zone, but in general and especially in recent years (1972-1977) the entire area has been affected at alarming rates. Bearing in mind that the ground elevation of 90 per cent of the land between the city and the coastline does not exceed 1 m above sea level and that 20 per cent of the latter is below mean sea level, the situation is becoming more and more serious.

In the past, the main cause of subsidence was wrongly ascribed to gas exploitation. The analyses carried out, though not precisely quantified, allowed us to estimate its effective contribution to the subsidence. With no doubt gas extraction from the natural deposits contributes in some zones to increase land settlement, but it has had limited effects. For instance, by superimposing the subsidence contour map of the period 1949-1972 on that of the gas reservoir of Ravenna Field, a good correspondence is observed between the area of the traps and area of the lines of equal subsidence, both being elliptic and with their major axes oriented in a NW-SE direction (Bertoni, et al., 1973) (Figure 9.15.12).

Likewise a comparison of land subsidence and the piezometric level recorded between 1949 and 1972 along a line crossing the Ravenna Field and industrial zone (Figure 9.15.13) shows a secondary local maximum, A, of subsidence corresponding to the location of the gas reservoir, but there is no corresponding piezometric decline [for which a minimum does not exist]. On the other hand, the maximum, B, of subsidence over the industrial zone corresponds to the maximum of drawdown. However, this gas reservoir is practically depleted and in 1972 its development had already achieved 95 per cent of the potential productivity: therefore the present contribution of gas withdrawal is probably negligible.

Unfortunately little is known about the more recent offshore gas exploitations and consequently it is impossible to say how much they influence the sinking of the coastal areas. This matter requires further investigation.

Among the man-induced causes of subsidence it must be remembered that marsh-land reclamation occurred on a large scale in this territory. Since the reclamation works were completed a long time ago (over 50 years), the contribution of the fill should no longer have any influence in the subsidence occurrence.

Natural subsidence gives a nonnegligible contribution in the overall occurrence. The bench mark of Porta Adriana in the historical center provides a useful indication to quantify this

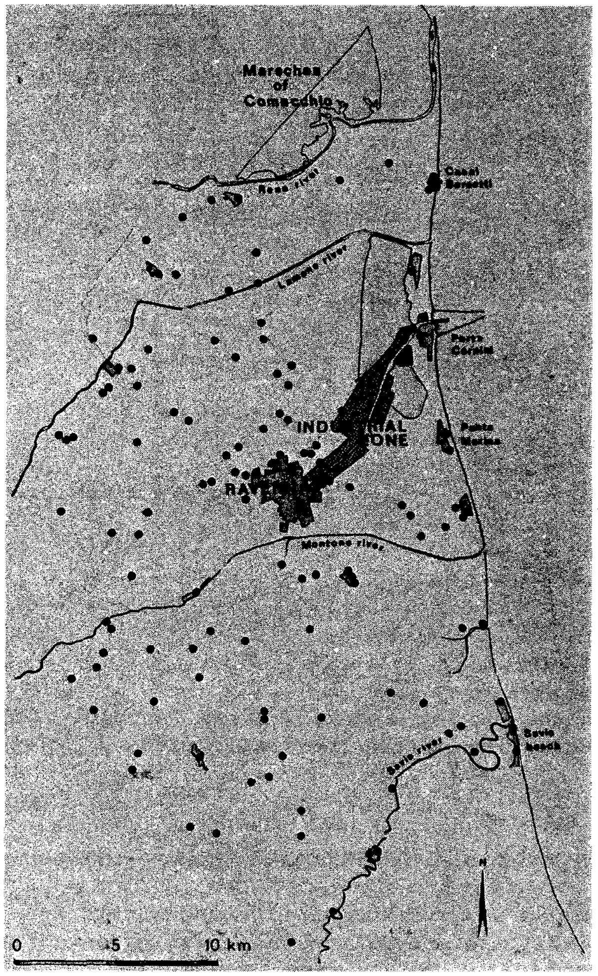

Figure 9.15.6 Map of the network of piezometers in the Ravenna area. (From Carbognin, et al., 1978, Figure 5; published with permission of the American Society of Civil Engineers.)

component since its elevation was recorded for the first time as early as 1902 (Figure 9.15.14). The data points of Figure 9.15.14 show that from 1902 to 1950 the subsidence rate was 5.14 mm/y (assuming as usual a linear trend in this period), while later on the rate has increased greatly due to the intensive exploitation of the subsurface resources. Since before 1950 water consumption was very small, the value of 5.14 mm/y may be considered as indicative of the geologic component of the subsidence in Ravenna.

To the present time the dominant factor of Ravenna subsidence is the intensive withdrawal of artesian water in the industrial zone, where the apex of the cone of depression is always found. The minimal piezometric levels reached in 1972 in the industrial zone have not changed but in spite of this additional subsidence occurred in the following years (Figure 9.15.15). This fact is partly explainable by a delay between the head declines in the aquifers and the resulting subsidence. As a second partial explanation it seems likely also that the maintenance of a very strong depression in the deepest aquifer over the last five years has introduced a secondary phenomenon of an upconing from the salt-water aquifers lying below 430 m, i.e., an irreversible pollution of the fresh-water system and a further compaction of the clayey soil aquitard. It is known in fact that some chemical variations of interstitial water in the clay soils can cause a change in the electrochemical equilibrium and therefore a collapse.

This contamination by salt water has been confirmed by the chemical analyses of the aquifer waters which evidence a progressive pollution in the industrial zone; this intrusion happened from the underlying saline water. In the nearby littoral, salt pollution of the same aquifer

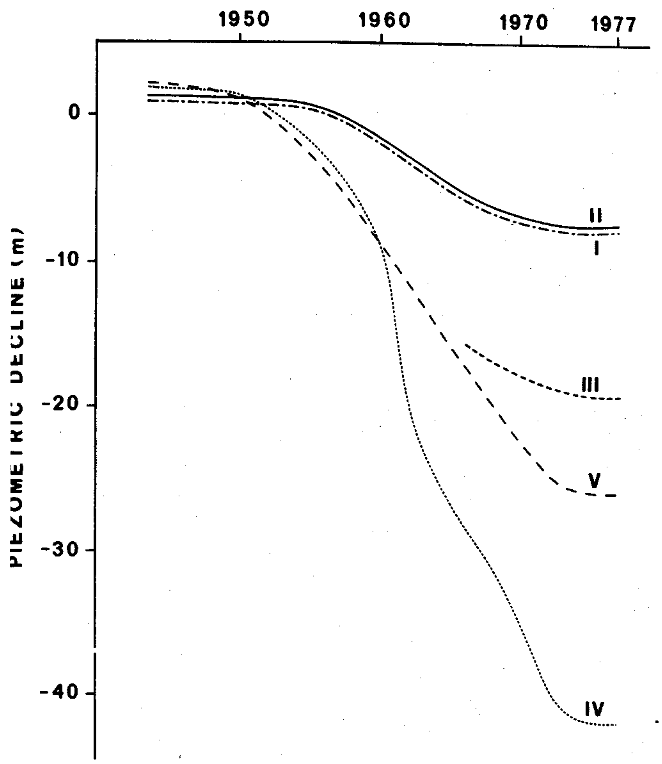

Figure 9.15.7 Piezometric levels from 1944 to 1977 of the various aquifers below the historical center of Ravenna. (From Carbognin, et al., 1978, fig. 6; published with permission of the American Society of Civil Engineers.)

occurred later but never reached the high values recorded in the industrial zone. In the coastal areas, salt water intrusion would also occur laterally.

As already shown in Figure 9.15.10b, the greatest sinking area after 1972 includes the coastline. The consequences are indeed very serious. In fact a striking regression of the shoreline and in some places the vanishing of the famous beaches of Romagna are the most severe effect of the sinking of the littoral. Not only coastal processes are responsible for it, as was believed before.

The following examples confirm the statement:

<u>Area of Lido Adriano</u>: From 1957 to 1977 the regression of the shoreline has been 126 m. In the same period this zone has experienced a subsidence of about 45 cm. With a 4 per mill mean average beach slope (computed up to the isobath -8), the subsidence prevails on the process of beach regression (Figure 9.15.16).

<u>Area of Punta Marina</u>: Between 1957 and 1977, the reported shoreline regression has been 70 m south of Punta Marina. The subsidence during these years has been 35 cm. Here the mean slope is around 4-5 per mill, and the beach regression is mostly attributable to the subsidence.

9.15.4 CONCLUSIONS

It is now clear that subsidence in the territory of Ravenna is mostly due to the intensive artesian water exploitation for industrial purposes, and, in more recent time, for agricultural uses. In some places the salt water intrusion has caused further compaction.

The exploitation of the gas reservoir of Ravenna Field has provided a minor local contribution to the subsidence; the possibility of a greater influence from the very active offshore gas fields is recognized and should be monitored.

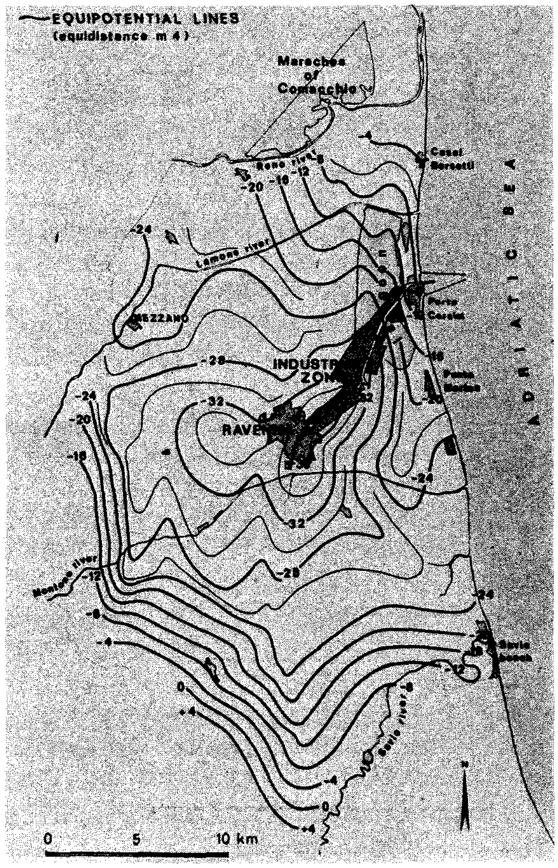

Figure 9.15.8 Average piezometric surface in 1977; datum is mean sea level. (From Carbognin, et al., 1978, Figure 7; published with permission of the American. Society of Civil Engineers.)

Since 1949 the average piezometric decline has nearly reached 45 m in the industrial area; correspondingly the average subsidence has been about 1 m. The close relationship between land settlement and water withdrawals has been clearly proven by the present analysis. Moreover if z indicates the land subsidence induced by man (i.e., the overall sinking minus geological component) and Δh is the piezometric decline expressed in the same units, we obtain a value $z/\Delta h$ approximately equal to 1/52. This result means that every 52 cm of withdrawal has produced 1 cm of subsidence. These values related to the environmental conditions place the Ravenna case among the more alarming in the world.

Apart from the values themselves, it is interesting to examine the trend of the occurrence. It is a matter of concern to find that while the subsidence still seemed quite localized around the industrial zone until 1972, it has assumed a broad increase since 1972. At present, the subsidence is affecting wide areas at a large rate and the related consequences are becoming highly critical for the survival of the whole physical and human environment.

The situation is very precarious along the littoral areas where a regression of the coastline over 150 m has been observed in some points. This threatens the most profitable industry of Romagna, i.e., the tourism.

The lands lying behind the coastal areas are in danger too. Bearing in mind that they lie at a height of less than 1 m above m.s.l., if the present trend is maintained for 10 years and if some sea storm would destroy the remaining dunes, 70 per cent of the territory between Ravenna and the beach (about 200 km^2) would permanently be inundated by the sea. Some urban zones, the industrial area, all harbor structures and several beach resort centers are in this part of the municipality. The damages would be incalculable. It is only a hypothesis, but not altogether unlikely.

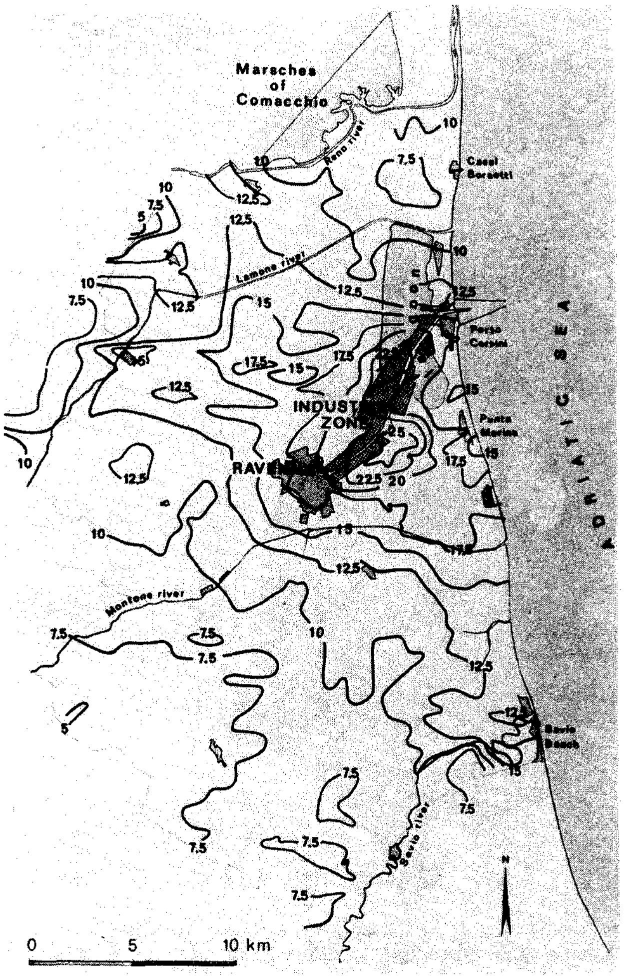

Figure 9.15.9 Land subsidence in the Ravenna area from 1972 to 1977, expressed in cm. (From Carbognin, et al., 1978, Figure 8; published with permission of the American Society of Civil Engineers.)

All this, however, is a simple projection of the present trend: a precise modeling is now in order. With enough information on physical and mechanical characteristics of the soils it would be possible to implement a mathematical simulation of the subsidence which would allow us to make real predictions on a long-term basis and understand the actual behavior of the system. In 1974 the authors (Carbognin, et al., 1974) suggested the necessary operations for investigating the knowledge on subsoil and improving the control of phenomenon evolution. In any case the subsidence control is today no longer achievable by local intervention, but only on a regional scale because of the vastness of the subsidence occurrence.

9.15.5 REFERENCES

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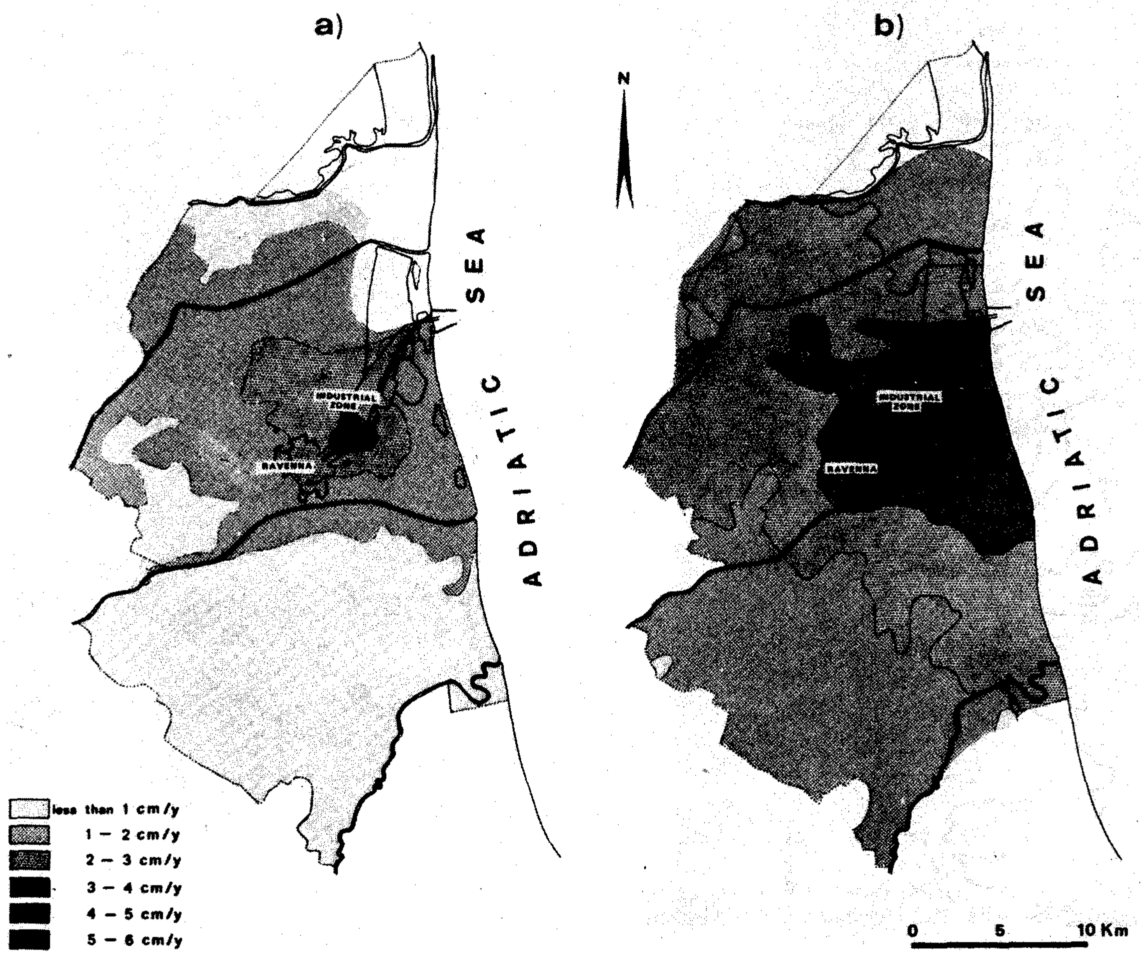

Figure 9.15.10 Space distribution of the subsidence rate between 1949-1972 (a) and 1972-77 (b). (From Carbognin, et al., 1978, Figure 10; published with permission of the American Society of Civil Engineers.)

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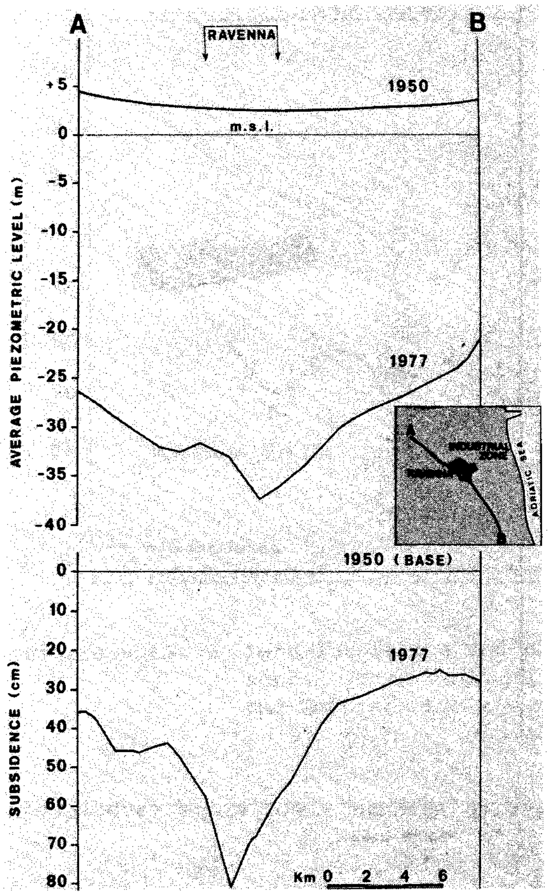

Figure 9.15.11 Comparison between the average piezometric level and the ground level over the city of Ravenna and its rural area. (From Carbognin, et al., 1978, Figure 9; published with permission of the American Society of Civil Engineers.)

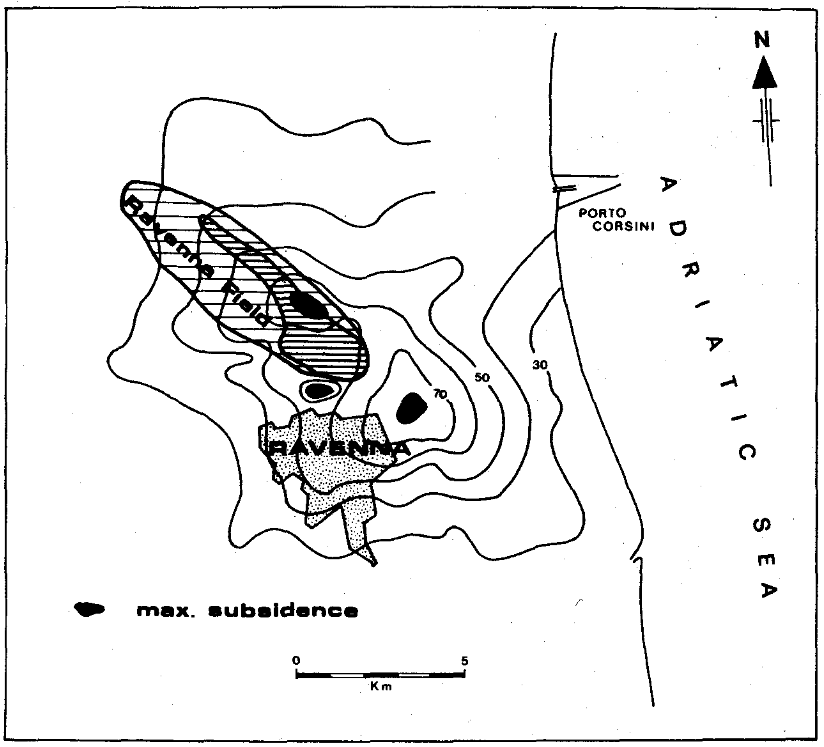

Figure 9.15.12 Comparison of development of sinking area with Ravenna Field traps (subsidence in cm).

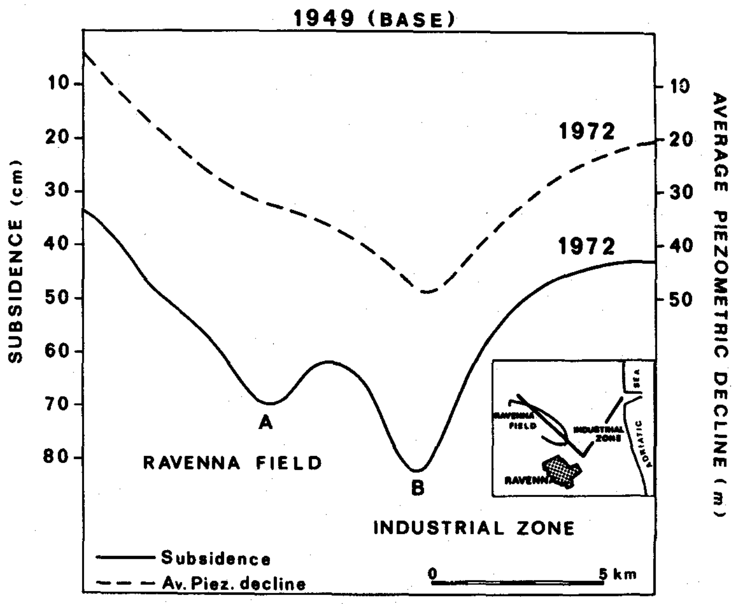

Figure 9.15-13 Land subsidence and piezometric level over the Ravenna Field and the industrial zone. (From Carbognin, et al., 1978, Figure 11; published with permission of the American Society of Civil Engineers.)

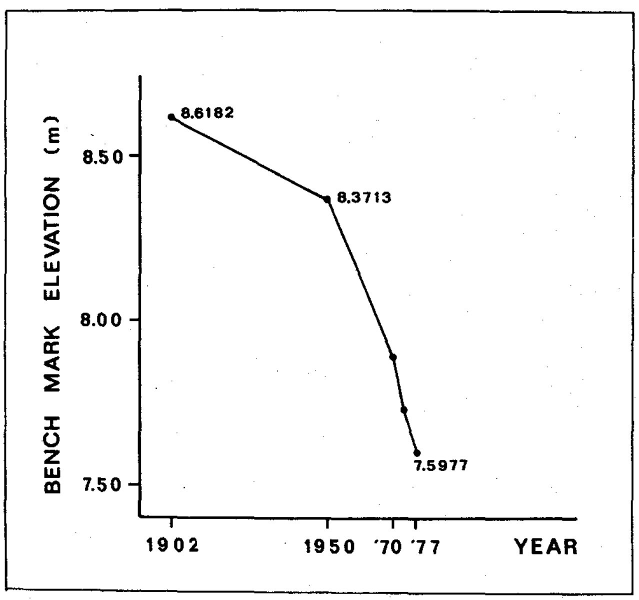

Figure 9.15.14 Elevation of bench mark of Porta Adriana (historical center) from 1902 to 1977.

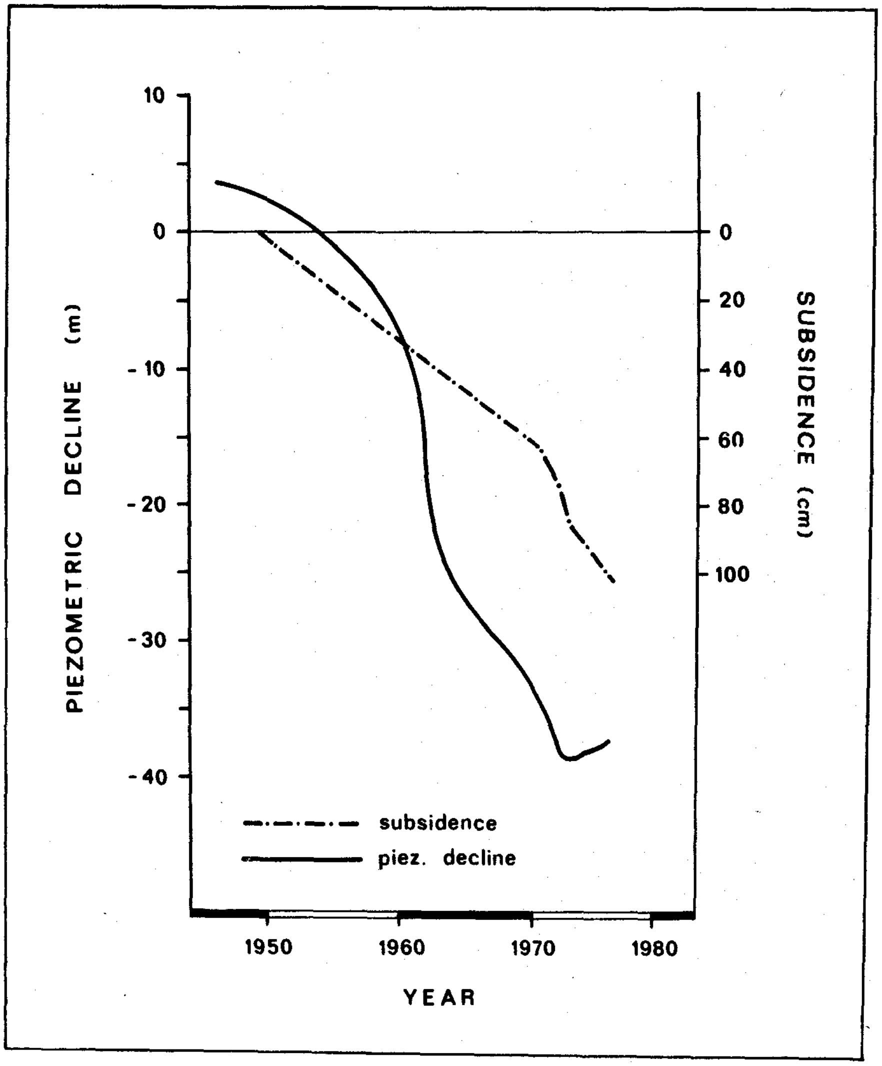

Figure 9.15.15 Comparison between subsidence and drawdown in the industrial area.

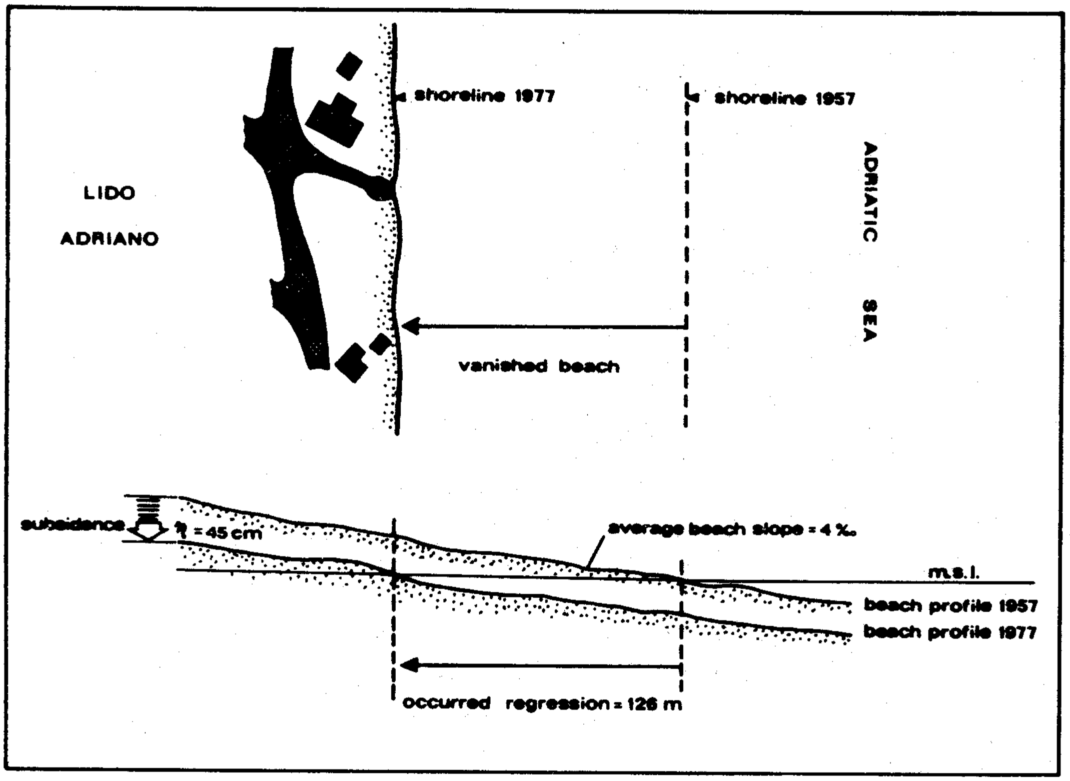

Figure 9.15.16 Schematic representation of the process of the beach regression at Lido Adriano area.