tion around raised-rim craters and is on a scale comparable to small martian craters. Thus, the flow field depicted (Fig. 1) appears to be valid for three scales of raised-rim crater—20 cm, 6 m, and 1.2 km—and can be used to explain the origin of the light and dark surface markings associated with the martian craters of Fig. 2. We do not imply, however, that all dark streaks are erosional and that all light streaks are depositional. It has been shown (*2*), for example, that some dark markings appear to be dune fields and hence are the result of deposition. It is likely that some dark and some light markings are erosional and others are depositional. Arvidson's (*10*) analysis of martian light and dark streaks indicates that many long light streaks associated with large craters appear to be erosional. Veverka (*11*) has shown Mariner 9 images on which at least one dark streak appears to be depositional. However, our studies apply to one specific category of crater (small, raised-rim) and each feature must be examined individually in terms of its size, shape, and relation to the surrounding topography in order to assess possible erosion and deposition.

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Predictive Simulation of the Subsidence of Venice

Abstract. *Land subsidence at Venice is the result of sediment compaction in the unconsolidated, aquifer-aquitard system that underlies the Venetian Lagoon. Compaction is caused by extensive groundwater withdrawals at the nearby industrial port of Marghera. The total subsidence at Venice for the period from 1930 through 1973 has been about 15 centimeters. Predictive simulations with a calibrated mathematical model were hampered by the sparseness of available data, but, as a first estimate, they suggest that, if withdrawals are kept constant in the future as they have been since 1969, about 3 centimeters of further subsidence can be expected.*

In recent years, worldwide attention has been directed toward Venice, where a collection of environmental problems threatens the existence of this historic and loved city. The problems are threefold. First, there is the periodic flooding of the city caused by the response of the Venetian Lagoon to tides and seiches in the Adriatic Sea; second, there is land subsidence under the influence of heavy groundwater withdrawals in the nearby industrial centers; and third, there is air pollution of industrial origin. In this report we summarize the results of an analysis of the second of these problems: land subsidence in the vicinity of the Venetian Lagoon. For a more complete treatment, the reader is directed to the detailed papers in *Water Resources Research* (*1, 2*).

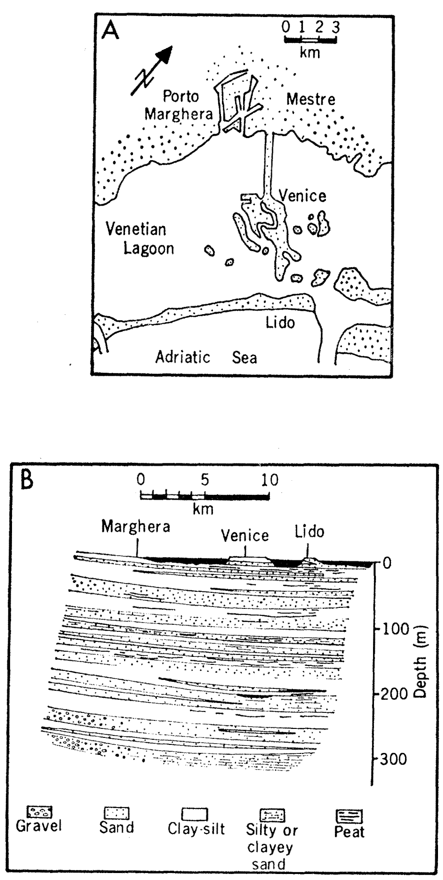

Fig. 1. (A) Location map. (B) Schematic stratigraphic section across the Venetian Lagoon; depth, 0 to 300 m.

The city of Venice occupies a canal-laced group of islands in the Venetian Lagoon, at the northwestern end of the Adriatic Sea (Fig. 1A). The cities of Marghera and Mestre lie on the mainland across the lagoon. The lagoon is shallow, and the sediments underlying it are an extension of those found on the plain that slopes down from the foothills of the Alps toward Venice. The geologic deposits in the upper 1000 m are unconsolidated sands, silts, and clays of Quaternary age.

At the industrial center of Porto Marghera, 7 km from Venice, there are large groundwater withdrawals from about 55 wells that tap five highly permeable aquifers in the upper 300 m. These water-bearing strata are continuous between Marghera and Venice. Extensive industrial pumping started at Porto Marghera in 1930, and by 1969 consumption had reached 460 liter/sec. Since 1969, no new wells have been drilled and pumpage has remained constant. In Venice itself, there is one major well, drilled in 1953, that extracts about 10 liter/sec (*3*).

The total amount of historical subsidence at Venice is not known exactly. It is only during recent years that detailed geodetic surveys have been carried out on a regular basis (1952, 1961, 1969). The observed subsidence during the period from 1952 through 1969 ranges from 9 to 11 cm in Venice and reaches a maximum of 14 cm at the center of the Marghera well field (*4*). These are small values in comparison with the 7- to 8-m subsidence reported for Mexico City and for Long Beach, California, but they are critical in view of the city's setting.

The rate of development of measured subsidence parallels the history of development of the Marghera well field. In light of similar interrelationships at many locations in the world (*5*) and considering the availability of an accepted theory to account for this interrelationship (*1, 6*), we believe that there is no doubt that the subsidence is caused by the groundwater withdrawals.

The mechanism that relates subsidence to withdrawal is that of subsurface compaction caused by changes in the groundwater flow field operating within the geologic system. The flow system is controlled by a potential field with the hydraulic head acting as the potential quantity. A practical measure of the hydraulic head at any point is the height reached by a column of water in a pipe tapping the geologic formation at that point. The introduction of a pumping well into a natural flow system produces a disturbance that propagates its effect in space and time through the hydrogeologic system. Around the well a cone of depression in the hydraulic head in the pumped aquifer develops and expands. The intensity of the head drop at any point in the system and the time lag between pumping and the arrival of the effect at the point depend on the distance of the point from the well field, on the geometry and geologic configuration of the subsurface basin, and on the hydromechanical properties of the geologic formations, in particular, their permeability and compressibility.

The reduction of the hydraulic head at any point in the system increases the effective intergranular stress in the formation at that point. This is so because the water can no longer support as large a percentage of the load of the overlying formations, and more of this load must now be borne by the grain-to-grain contacts of the geologic material itself. Under the influence of the increase in effective stress the formations compact, with the amount of compaction being proportional to the compressibility of the compacting unit.

Aquifers of sand and gravel, which are the formations generally tapped by wells, compact almost elastically, and their compaction is generally small owing to their low compressibility. The clay and silt units, or aquitards, that separate the aquifers have much larger compressibilities, and these are the formations that provide the most significant compaction. Their compaction is mostly nonrecoverable since their compressibility in expansion is usually about 0.1 of that in compression. In summary, withdrawals of groundwater cause reductions in the hydraulic head, increases in the effective intergranular stress, and compaction. The subsidence at the surface is the sum of the subsurface compactions of the various formations.

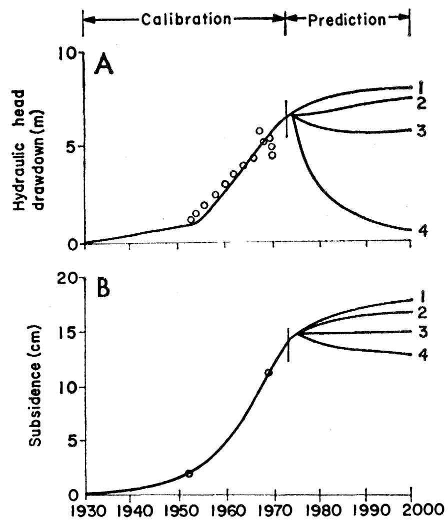

Fig. 2. (A) Calibrated hydraulic head drawdowns at Venice in the aquifer at 100-m depth during the calibration period from 1930 through 1973 and predicted hydraulic head variations for the period from 1973 through 2000 under several possible future pumping schedules. (B) Calibrated total subsidence at Venice during the calibration period from 1930 through 1973 and predicted total subsidence for the period from 1973 through 2000 under several possible pumping schedules.

Figure 1B is a schematic diagram of the detailed stratigraphy in the upper 300 m at Venice. Withdrawals at Marghera are taken from the various sand and gravel aquifers. Most of the compaction beneath Venice occurs in the intervening silt and clay aquitards.

We have analyzed the subsidence at Venice with a two-step mathematical model. In the first step (the hydrologic model) we have calculated the regional hydraulic head drawdowns in a two-dimensional vertical cross section in radial coordinates, using a model that is a boundary-value-problem based on the partial differential equation of groundwater flow (a form of the diffusion equation), and solved with a numerical finite-element technique. The radial section is centered in Marghera and lies along a line from Marghera to Lido through Venice (Fig. 1A). The base of the section has been taken at a depth of 300 m, below which a massive silty unit of low permeability occurs. For the purposes of the hydrologic model we have generalized the geologic configuration into five aquifers and four intervening aquitards. The forcing function is the time-dependent withdrawal rate at Marghera. Before using the model in a predictive capacity, it was first necessary to calibrate it in terms of the regional formation parameters (permeability and compressibility) of each of the geologic formations. This was done with a trial-and-error procedure in which various possible combinations of values (in keeping with the ranges of values suggested by the rather sparse available data) were tested to see which provided the best fit to the past observed records of hydraulic head decline at Venice.

In the second step of our procedure (the subsidence model) the hydraulic head declines determined with the calibrated hydrologic model were used as time-dependent boundary conditions in a set of one-dimensional vertical compaction models applied to a more refined geologic representation of each aquitard. The subsidence model is a boundary-value-problem based on the one-dimensional equation of flow and solved with a finite-difference technique. A test hole drilled in the Tronchetto area of Venice provided the detailed multilayer configurations within the aquitards, and laboratory measurements of the physical properties of each layer were made on samples taken from the test hole. These values were slightly modified within their local ranges of variation in a trial-and-error calibration of the subsidence model against the subsidence record for 1952 through 1969.

Figure 2 shows some of the results of our simulations, both for the calibration period and for the prediction period. Figure 2A displays the output from the hydrologic model for one of the five aquifers. The calibration portion on the left shows the hydraulic head drop at Venice for the period 1930 through 1973, as provided by the mathematical model and as calibrated against the available records. Similar profiles hold for the other aquifers. The left side of Fig. 2B shows the computed subsidence at Venice. For the period 1930 through 1973 a value of 15 cm is indicated. The single well in Venice exerts a modest influence on the subsidence, but the main responsibility for Venetian subsidence can be placed on the heavier industrial pumpage at Marghera.

The right side of Fig. 2, A and B, shows the predicted changes in hydraulic head and subsidence (or rebound) under a variety of possible pumping schedules. We did not investigate any future pumping schedules that allow increases in withdrawals because it is clear that the resulting subsidence would be unacceptable in view of the precarious island setting of Venice. If the consumption in both Marghera and Venice is held constant from 1973 onward as it has been since 1969, about 3 cm of further subsidence is to be expected (curve 1). A complete cessation of the Venice extraction alone in 1974 would save about 1 cm of this (curve 2). If the Venice pumping were stopped in 1974 and the Marghera consumption reduced to 0.75 of its present value, the subsidence at Venice would be arrested at essentially its present value (curve 3). A shutdown of all wells in 1974 would arrest the subsidence at its present level and would provide a modest rebound of perhaps 2 cm in the next 25 years (curve 4). Artificially recharging the depleted aquifers would increase the rate of rebound but not the ultimate amount. Over 85 percent of the Venice subsidence is nonrecoverable.

The predictions presented in this study are based on a model calibration that was hampered by the sparseness of available data. These predictions should be viewed as first estimates that may require substantial modifications as further data become available. They are not firm enough to allow the conclusion that subsidence is no longer a problem in the Venice area. We recommend continued data acquisition and continued evaluation of the Venice subsidence situation.

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Leprosy in the Armadillo: New Model for Biomedical Research

Abstract. *Eight of twenty armadillos* (Dasypus novemcinctus *L.*) *developed severe lepromatous leprosy 3 to 3.5 years after inoculation with viable* Mycobacterium leprae. *A total of 988 grams of lepromas containing an estimated 15 to 20 grams of leprosy bacilli has been harvested from these animals. The large amounts of material now available will permit in-depth studies of the biochemistry and metabolism of the leprosy bacillus, and the animal model should make possible definitive studies on the immunology, chemotherapy, and epidemiology of the disease.*

Leprosy is one of the major public health problems in the world today. The study of leprosy has been seriously impeded by the fact that the causative agent, *Mycobacterium leprae*, cannot be grown in artificial media and that, until recently, only a mild infection with microscopic lesions could be obtained in immunologically intact animals. This has left many unanswered questions relating to the epidemiology of the disease (modes of transmission, effects of genetic and nutritional factors, and so forth) and also has resulted in slow progress in the search for drugs to halt the disease process quickly and effectively. In addition, the limited amounts of *M. leprae* available have not been sufficient for in-depth biochemical and metabolic studies of the organism, studies that are necessary for a complete understanding of the disease.

Leprosy is classified with the granulomatous diseases; because of the diverse manifestations in individuals infected with *M. leprae*, leprosy qualifies as a complete model for the study of granulomatous diseases. Resistance to leprosy appears to be primarily regulated by cell-mediated immunity—the same immunologic machinery that is thought to control neoplastic growth and the rejection of foreign tissue transplants and of other infectious agents (viruses, fungi, and so forth).

Storrs (*1*) and Kirchheimer and Storrs (*2*) reported the development of leprosy in a single nine-banded armadillo (*Dasypus novemcinctus* L.) 15 months after inoculation with leprosy bacilli obtained from a human patient. Postmortem examination and subsequent histopathological evaluations confirmed the presence of advanced, disseminated leprosy in this animal (*3*). Thirty-three other armadillos have developed lepromatous leprosy, 11 of which have been necropsied and subjected to histopathologic examinations. These have yielded a total of 1235 g of granulomatous lepromas.

The average survival time of the adult animals from inoculation until death from leprosy or its complications appears to be about 31 months. Therefore, the only significant information on the incidence of susceptibility of the armadillo to leprosy and the severity of the disease in this species can be obtained from three groups totaling 20 animals which were inoculated with viable bacilli in February and June of 1970 (Table 1).

All animals in these groups were adults captured from the wild and adapted to captivity for at least 6 months before inoculation (*4*). The inoculum was one of the following: leprosy bacilli from an untreated lepromatous leprosy patient from Surinam; *M. leprae* (supplied by the Public Health Service Hospital in Carville, Louisiana) from a patient who was not responding to drug (Dapsone) therapy; and human bacilli grown in the mouse foot pad (supplied by L. Levy of the Public Health Service Hospital in San Francisco, California).

Suspensions of these materials were inoculated by three routes: intradermal injection of 0.1 ml in the abdomen (right and left sides), ear lobe, or foot

Table 1. Data on inoculum and number of animals developing leprosy.

Group	Animals per group			Inoculum		Animals developing leprosy	
	Total	♂	♀	Source	Bacterial count (acid fast bacilli per milliliter)	No.	%
1	4	3	1	Human	8.9×10^7	2	50
2	3	2	1	Human	6.0×10^6	1	33
3	13	7	6	Mouse*	1.4×10^6	5	40
Total	20					8	40

* Mouse foot pad passage of human *M. leprae.*