7 Review of methods to control or arrest subsidence, by Joseph F. Poland and Working Group

7.1 SUMMARY OF AVAILABLE METHODS

7.1.1 General statement

Methods to control or arrest subsidence include reduction of pumping draft, artificial recharge of aquifers from the land surface, and repressuring of aquifers through wells, or any combination of these methods. The goal is to manage the overall water supply and distribution in such a way that the water levels in wells tapping the compacting aquifer system, or systems, are stabilized or raised to some degree. In other words, at least manage the overall supply in such a way that effective stress in the aquifer system is not increased beyond the stress experienced to date.

The local geologic conditions determine whether artificial recharge can be accomplished by regulated application at the land surface or by repressuring of aquifers by means of injection through wells.

Both the artificial recharge of aquifers from the land surface and the repressuring of aquifers through wells normally require a supply of potable surface water. The question may be asked: "Why not use the supplementary surface supply directly at land surface and thereby reduce ground-water draft, instead of recharging the ground-water supply?" The answer may be that it is impracticable to deliver all the supplementary supply direct to users so part of the supply is recharged to the water table. The ground-water reservoir then acts as the distribution system. Such is the case in the Santa Clara Valley in California (Case History 9.14).

7.1.2 Reduction of pumping draft

Reduction of pumping draft may be accomplished to some degree by one or more of the following methods:

1. Import of substitute surface water.
2. Conservation in application and use of water:
   a. through improvement of irrigation methods, such as change from ditch and furrow or flood irrigation to overhead sprinkler irrigation or to drip irrigation.
   b. through change from crops requiring heavy duty or demand to crops requiring less duty, such as from cotton to orchards.
3. For overdrawn ground-water basins, adjudication (equitable distribution) of available supply.
4. In urban areas, by recirculation and reuse of treated water by industrial plants.
5. By decreasing irrigated area or industrial plants using large quantities of water.
6. By moving the well fields to tap more permeable (less compressible) deposits.
7. By changing the depth range of perforated intervals in well casings or screens to tap less compressible deposits.
8. By legal control.

Whether any one of these remedies is economically justified depends on its cost compared with the costs of continued subsidence. The first requirement for estimating costs is an estimate of the magnitude of subsidence that would occur (1) if the artesian head was maintained at the present level, and (2) in response to an assumed additional decline in head.

7.1.3 Artificial recharge of aquifers from the land surface

Land subsidence usually results from compaction of compressible confined aquifer systems due to intensive withdrawal of ground water and consequent decline of artesian head. Because confining beds restrict the vertical downward movement of water from the land surface, artificial recharge of confined system(s) by application of water at the land surface directly overhead ordinarily is not practicable. However, the geology of the system may be such that the confined aquifer system may crop out at or near the margins of the ground-water basin; this outcrop area may be near enough to the subsiding area so that artificial recharge on the outcrop area will raise the local water table and also the artesian head in the confined system.

7.1.4 Repressuring of aquifers through wells

Repressuring of confined aquifer systems by artificial recharge directly through wells, although expensive, may prove to be the only practical way to slow down or stop land subsidence in a particular area. The Wilmington oil field in southern California is a classic example of subsidence control by injection of water through wells. Repressuring of the oil zones to increase oil production and to control subsidence began on a major scale in 1958. By 1969, when 175 x $10^3 m^3$ (1.1 x 10^6 barrels) of water per day was being injected into the oil zones, the subsiding area had been reduced from 58 to 8 km^2, and locally the land surface had rebounded as much as 0.3 m (Mayuga and Allen, 1969). In 1975 about 80 x 106 m^3 (500 x 10^6 bbls) of water was injected into the oil zones to (1) control subsidence, (2) produce 10 x 10^6 m^3 of oil and (3) utilize 67 x 10^6 m^3 of water produced with the oil. According to Gates, Caraway, and Lechtenberg (1977), the injection of this great quantity of water from diverse sources created many problems which were controlled by various chemical and physical treatments.

Replenishinq ground-water supplies by artificial recharge through wells and pits has been practiced in many areas, including many sites in California and more than a thousand recharge wells on Long Island, New York. The results of such practices have been summarized to 1967 in two annotated bibliographies on artificial recharge of ground water (Todd, 1959; Signor, Growitz, and Kam, 1970). In general, results were satisfactory when the water was clear; most of the problems of recharge through wells involved clogging of the well and aquifer. In a study of problems in artificial recharge through wells in the Grand Prairie region of Arkansas, Sniegocki (1963) found that the principal causes of clogging were air entrainment, suspended particles in the recharge water, and micro-organisms. He concluded that wells should be recharged with treated water and that water-treatment cost and contemplated use of the recharged water are the principal factors involved in determining the economic feasibility of artificial recharge. The availability of water suitable for injection would be another important factor.

Injection of treated fresh water into a confined aquifer system to create an hydraulic barrier (pressure ridge) to sea-water intrusion has been practiced successfully in southern California for 25 years. The operating agency, the Los Angeles County Flood Control District, had 180 injection wells in operation in 1976. According to Rancilio (1977), during two decades of operating experience the District never has had to cease operation of an injection well permanently because of loss of operating efficiency. Because of the continuing success of this massive injection operation for a quarter century, the reader interested in injection wells is referred to the paper by Rancilio (1977) which describes in detail the typical design of a successful injection well, operating conditions and costs, injection rates and heads, clogging problems, and redevelopment of injection wells. Both the cable-tool and reverse-rotary methods were used in construction of the injection wells but at least two-thirds of the wells are reverse-rotary, with asbestos-cement casing and gravel pack. The operational injection heads ranged from 9 to 61 metres and injection rates ranged from 6 to 28 l/s.

7.2 REVIEW OF METHODS USED

7.2.1 Summary statement

Table 1.1 lists 42 areas of land subsidence due to ground-water withdrawal. Methods used to control or arrest subsidence in these areas may be summarized as follows:

In 15 areas, ground-water draft has been reduced as a result of substituting imported or locally treated surface water.
In 4 areas, ground-water draft has been reduced by regulation but surface water import not reported.
In one area, pumping of gas-bearing water was stopped by legal action (Po Delta, Italy); in another area (Niigata, Japan) reinjection of all gas-bearing water has been required since 1973.
In one area, ground-water pumped from mines has been led outside rock compartments or injected into a leached dolomite aquifer through 10 boreholes since 1973.
In 20 areas no methods for control have been reported.

7.2.2 Shanghai, China

Land subsidence in Shanghai, China, was first reported in 1921. By 1965 the maximum cumulative subsidence in the city was 2.63 m (Case History 9.2). Injection of river water through wells to recharge the principal aquifers began about 1964. By 1966, more than 100 industrial plants operating more than 200 wells had joined in the recharge operation to build up pressure in the confined aquifer system. As shown by the record from typical bench marks in the urban area of Shanghai (Figure 9.2.1), the cessation of subsidence was virtually instantaneous. Within a year or two, bench marks apparently were rising and from 1966 to 1976, as much as 34 mm of rebound occurred.

The injection of river water through production wells is undertaken chiefly in the winter months when many factories are not operating and when the river water is coldest. Because much of the ground water withdrawn is used for cooling purposes in the factories in the summer, any decrease in water temperature in the aquifers is beneficial. As a result of careful monitoring of river-water temperature to obtain water of minimum temperature for injection, the ground-water temperature at one site reportedly has been lowered 6° C.

7.2.3 Venice, Italy

After studying by mathematical model the physical mechanism and the quantitative relationship linking the pumping rate to the resulting subsidence of Venice, the behavior of the aquifer system and ground surface became well understood. (See Case History 9.3.) Because land subsidence was caused by pressure drawdown in the aquifer system, it was apparent that the only remedy consisted of raising the pressure surface beneath Venice.

Injection of water through injection wells was suggested as a possible measure by a number of experts. However this solution would have required water with chemical properties similar to those of the underground water. Moreover the effectiveness of this remedy could not be scientifically proven.

An uplift experiment on a small island near Venice was successfully carried out by pressure grouting using special cement mortars (Marchini and Tomiolo, 1977). Unfortunately, the experiment could not be transferred to uplift such an extensive area as Venice.

Other proposed solutions, including the construction of a deep wall acting as a hydraulic barrier for the city, were soon abandoned on the grounds of impracticability.

The recognition of the physical mechanism underlying the subsidence of Venice and the results provided by theoretical and experimental patterns showed that the most effective and cheapest solution consisted of reducing the withdrawal rate in the Venetian area. The recovery of the flow field was shown to be rather fast and the arrest of the settlement was proven to be almost instantaneous.

Accordingly, the Venice Municipality prompted the completion of the planned aqueduct and the construction of a new one to supply the industrial area with water taken from the Sile and the Brentella Rivers, which flow in the vicinity of the Venetial Lagoon. More that 90 per cent of the water used for industrial purposes now is supplied by surface water from the local rivers. Furthermore, as soon as the aqueducts became operative, the Magistrato alle Acque (Civil Engineers Branch) of Venice issued a prohibition against opening new wells and an injunction to close the existing wells.

To date, more than 70 per cent of the artesian wells that were active in 1969 have been gradually shut down; this trend still continues and a constant improvement of the subsidence situation in Venice has been observed (see Case History 9.3)

7.2.4 Japan

The ten principal subsidence areas in Japan, due to excessive ground-water withdrawal, are listed in Table 1.1. In all of these areas ground-water withdrawal has been reduced by regulation; in parts of Tokyo withdrawal of ground water from wells has been prohibited completely. (See Case History 9.4). In seven areas surface water has been imported as a replacement for ground water. In several areas, industrial waste water is being treated and reused.

In Niigata (Case History 9.7) experiments of water injection into the confined aquifers containing methane gas were carried out from 1960 to 1963 (Ishiwada, 1969). The purpose of the injection was the maintenance of reservoir pressures and reduction of the rate of subsidence. Both degassed formation water and river water were used as the injection fluids. According to

Ishiwada, the permeability of the main reservoirs ranges from 10 to 50 darcys, the injection rate is less than one-quarter of the production rate, and back-washing at adequate time intervals is necessary to continue long-term injection.

Since 1973, all degassed formation water has been reinjected into the gas-bearing reservoirs by law.

7.2.5 United States

Table 1.1 describes 18 areas of land subsidence in the United States. Of these, six have imported surface water to satisfy water demands. This has led to the reduction of pumping draft and the local stabilizing or raising of artesian pressures. They include the Santa Clara Valley and three areas in the San Joaquin Valley in California, as well as Las Vegas Valley in Nevada and the Houston-Galveston area in Texas. A major aqueduct to import Colorado River water to south-central Arizona now (1980) is under construction.

Repressuring through injection wells has not been used in any of these areas and artificial recharge of a substantial part of the imported surface water has been practiced only in the Santa Clara Valley. In the other five areas, imported surface water has been used as a direct replacement or substitute for ground-water pumpage.

7.3 REFERENCES

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