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INTRODUCTION

The City of Tucson, Arizona, population 260,000 is unique among cities of comparable size in the United States in that water requirements are satisfied entirely by pumping from ground water. Increasing demands are being placed on this supply by burgeoning municipal and industrial requirements in the metropolitan area and by agricultural uses in the environs. Recharge occurs during influent seepage in the Santa Cruz River, an ephemeral stream passing through the city, and its tributaries during flash floods. Except for unusual runoff periods, however, such as those in 1965–1966, the magnitude of recharge does not keep pace with withdrawals. Consequently, water levels are dropping in the Tucson Basin at an average rate of about one m/yr (Matlock, *et al.* 1965). In order to ameliorate the draft on ground water, increasing emphasis is being placed on conservation of sewage an industrial effluent. Artificial ground water recharge constitutes one effective method for conserving these supplies.

Water spreading, the simplest method of artificial recharge, consists of flooding the soil surface at the recharge site; thereby inducing percolation into ground water. This method is restricted to land areas not suitable for cultivation or other uses, and on highly permeable materials with an absence of impeding layers. Water spreading has been employed effectively in Los Angeles, California (Todd, 1959). The pit method of recharge is used when shallow strata preclude the use of water spreading facilities. Results of studies at Peoria, Illinois (e.g., Suter, 1956) have provided extensive clues on the design, construction and management requirements for pit recharge. This method is used in several areas of the United States, such as Texas and New Jersey, to recharge excess surface runoff. Well injection, a third method of artificial ground water recharge, is employed when geologic materials are stratified or where scarcity of land prohibits the use of other methods. Well recharge is used in the Los Angeles area of California to promote the development of a fresh water barrier against sea water intrusion (Bruington and Seares, 1965). Dual purpose irrigation-recharge wells are used in the High Plains of Texas to recharge playa lake water into the Ogallala formation, which is being depleted by excessive pumping (Valliant, 1962). Experiences and technical requirements for well recharge in Israel have been reported by Sternau (1967).

The artificial recharge investigations cited above have yielded valuable information on the rational design of recharge facilities for the geologic condition of the specific areas involved. Comparable studies for the Basin and Range sediments of the Tucson Basin are limited. In particular, data are lacking on the design of recharge wells. Such data are required for the effective utilization of wells in a conservation program.

This paper summarizes the methods used to design an experimental recharge well at the Water Resources Research Center Field Laboratory, The University of Arizona, Tucson, Arizona. Construction details are presented, together with results of preliminary recharge trials using an industrial waste effluent.

Location: Tucson, Arizona is located in the southwestern United States: latitude 32° 14′ N; longitude 110° 57′ W; altitude 732 meters above sea level. The climate of Tucson is classified as semi-arid; the mean annual temperature and the average annual rainfall are about 20°C and 28 cm, respectively. Precipitation occurs primarily during the summer, as a result of convective storms, and in the winter, as a result of cyclonic storms. The Tucson Basin, of the Upper Santa Cruz River Basin, is a part of the Basin and Range Physiographic Province of the United States. A characteristic of this province is that valley troughs have been filled with detritus from the surrounding mountains. These sedimentary deposits are heterogeneous and highly stratified, but contain productive aquifers. The Tucson Basin is encircled by the Santa Catalina, the Tucson, and the Rincon Mountains. The valley floor is relatively flat. Water levels in spring 1966 ranged from 21 m to 30 m below ground surface (Hodges, *et al* 1967).

Agricultural development in the area consists primarily of the production of cotton, sorghums and barley. The Water Resources Research Center Field Laboratory is located near the northwestern boundary of the City of Tucson on about four hectares of an Agricultural Experiment Station of The University of Arizona. The research area is contiguous to the Santa Cruz River.

METHODS AND MATERIALS

The design of an artificial recharge well should be based on a sound knowledge of the hydrogeology of subsurface materials at the proposed site.

Information may be obtained by, (1) examining drillers' logs from water supply wells in the vicinity of the site; (2) drilling special wells for detailed observation of lithology; (3) geophysical exploration; and (4) observations on subsurface flow. These methods were all employed for the design of recharge well at the Water Resources Research Center Field Laboratory.

1. Drillers' logs : A water supply well was constructed at the WRRC Field Laboratory about 153 m northwest of the site of the proposed recharge well. The well was installed by percussion (cable tool) drilling to a depth of about 90 m below ground surface. A log of subsurface materials was maintained by the driller during construction. This log indicated major changes in stratigraphy and the depth to water.

2. Construction of special wells : Three 20.3 cm observation wells, each 46 m deep, were constructed by the percussion drilling method at the experimental site to provide specific data on lithology. These wells were installed 4.6 m west, 54.9 m south, and 76.2 m northwest, respectively, of the proposed recharge well. During construction, observations were made on drilling rate and the appearance of bailed drill cuttings. Sieve analyses were conducted on samples obtained in 1.5 m increments.

In addition to the observation wells, ten access wells, consisting of 5.03 cm O. D. seamless steel tubing, were installed to a depth of 30.5 m at various distances in an array around the site of the proposed well. These wells were constructed for use with a neutron moisture logger, but drill cuttings were obtained for observations of lithological changes.

3. Geophysical exploration ; Geophysical explorative techniques at the research site included natural gamma logging in observation wells and access tubes and development of resistivity profiles using a resistivity meter. The results of these tests were correlated with the sieve analysis and other data obtained during construction of the wells to gage the spatial distribution of various stratigraphic units at the site.

4. Subsurface flow characteristics : Clues on the distribution and rates of water movement through the vadose region at the site were obtained from neutron moisture logs in access wells, using a Well Reconnaissance Inc., of Dallas, Texas, logger (source of high energy neutrons : 100 m.c. Americium-Beryllium). Particularly useful observations were obtained during natural recharge in the Santa Cruz River and during artificial recharge studies in a recharge pit at the site.

A preliminary estimate of the transmissivity of materials in the phreatic region was obtained from a pump test in the water supply well. Additional data were obtained on the specific capacity (i.e., yield per incremental change in drawdown, $m^3/hr/m$) of the well. Specific capacity data provide estimates of the potential intake rate for a recharge well of the same diameter.

5. *Appurtenant facilities and effluent supply :* In addition to the observation wells and access wells, other facilities are available at the Water Resources Research Center Field Laboratory for use in conjunction with the recharge well. The appurtenaces include a stabilization chamber, for dampening head fluctuations in the incoming effluent; a low-lift pump assembly; a distribution pipe line from the stabilization chamber to the recharge well, including control valves and a propeller flow meter; and a gaseous chlorinator.

The water supply for recharge trials is an industrial waste effluent from the Tucson Gas and Electric Co., Grant Road Plant. The effluent consists of a blend of blow down effluent from cooling towers at the plant and higher quality effluent from an adjoining transformer station. The discharge rate of the blend averages about 91 m^3/hr. Salt concentrations vary from 800 mg/l to more than 2000 mg/l. The corresponding salinity of the native ground water at the research site averages about 1100 mg/l, and the ionic constituents are similar to those in the blended effluent. The sediment content of the effluent is insignificant. The blended effluent is transported a distance of 1280 m to the Water Resources Research Center Field Laboratory in a closed pipeline.

RESULTS

1. *Stratigraphy :* Analysis and observation of drill cuttings from the water supply well, observation wells and access tubes in and near the study area, together with other observations during drilling, consistently manifested the presence of three sedimentary units, (a) Alluvium, extending from land surface to a depth of about 9.1 m, consisting of fine grained soil material in the upper 3.0 m and relatively permeable gravels and pebbles in the lower 6.1 m; (b) Basin Fill materials, extending from 9.1 m to about 24.4 m below land surface, consisting of beds of silt, sand, gravel and boulders, apparently somewhat less permeable than overlying materials; and (c) Older Sediments, extending from 24.4 m to an unknown depth, consisting of interbedded deposits of silt, sand and gravel, relatively permeable in the upper zones. Correlative data using sieve analysis, natural gamma logs and resistivity profiles indicated that these stratigraphic features are apparently spatially uniform throughout the area. Depth to water levels in wells averaged about 24.4 m below ground surface.

2. *Subsurface flow characteristics* : Clues on the permeability of sediments and subsurface flow patterns within the vadose zone were obtained at the site during influent seepage in the Santa Cruz River for runoff events in 1965-1966 and during pit recharge studies in 1966. Two mounds were apparent in the vadose zone from moisture logs in access wells, (a) an upper mound extending through permeable materials in the basal portion of the Alluvium unit into materials in the upper portion of the Basin Fill unit, and (b) a lower mound extending through the lower materials of the Basin Fill unit. The growth of these mounds occurred rapidly; observations indicated that the mounds spread inland at about 61.0 m per day. Water from these mounds drained slowly into the phreatic region at 24.4 m

The transmissivity of phreatic aquifer materials, calculated from the results of pump tests in the water supply well, was found to be about 670 m^2/day. The specific capacity of the well was about 18.6 m^3/hr/m.

3. *Design and construction of recharge well* : The hydrogeologic observations discussed above were used to design the experimental recharge well. Thus, based on the observation that materials in the vadose zone are highly permeable, it was elected to construct a "dual" recharge well to recharge the unsaturated region as well as the phreatic zone. For best results, materials and drilling methods for well construction should be those commonly employed by drillers in the area. Consequently, the recharge well in Tucson was constructed from steel casing using percussion drilling. Drill cuttings were obtained during construction for sieve analysis, and observations were made on drilling rates and appearance of baled samples. Upon completion and cleaning of the well, a test pump was installed to develop aquifer materials in the phreatic region and there by optimize intake rates. Initial data were obtained on the specific capacity of the well.

A cross section of the "dual" recharge well is illustrated in Figure 1. The 50.8 cm diameter well was installed to a depth of 45.7 m with 0.3 m projecting above land surface. The steel casing was perforated in two sections : from 6.1 m to 11.9 m, in permeable, unsaturated materials of the Alluvium and Basin Fill units; and from 24.4 m, the normal water level, to 39.6 m below land surface, in the older Sediments stratigraphic unit. Perforations consist of milled slots machined in the casing prior to installation. The location, size and number of perforations were determined from the results of particle size analysis of materials in the perforated regions in accordance with commonly used methods (Todd, 1959). Machine milling provides very accurate control on the dimensions of perforations. Consequently, it was possible to calculate precisely the total open areas of perforated regions: 1890 cm^2 and 4554 cm^2 for the upper and lower zones, respectively.

Sections of 5.1×5.1 cm angle iron were welded onto the exterior of the casing to facilitate measuring water levels outside the casing at both recharge sections. A grout seal was installed around the upper 4.6 m of casing to minimize upward leakage during recharge.

In order to recharge the upper zone independently of the lower zone, a liner and packer assembly were installed within the well. The liner was constructed from 18.3 m of 30.5 cm diameter steel casing. The packer assembly was fabricated using a neoprene rubber washer sandwiched between two steel washers welded near the end of the liner. The liner and packer assembly were lowered inside the 50 8 cm casing to the depth shown on the figure, with the upper 0.3 m of the liner extending above the top of the casing. A steel washer was welded to the casing and liner to provide support.

Inlet facilities are shown on figure 1. Access to the annular region between the casing and liner for recharge to the upper zone was provided by welding a 10.2 cm inlet pipe onto the well casing. Similarly a 10.2 cm pipe was welded onto the liner to facilitate recharge to the lower region.

A pumping plant was installed in the well for redevelopment of the well, subsequent to recharge tests, and for auxiliary studies. The unit consists of a deep well turbine pump with a 20.3 cm discharge column and three 25.4 cm diameter bowls set at 42.7 m; and a right angle gear drive assembly. The power plant is a natural gas engine. The 20.3 cm discharge line contains an inlet from the effluent supply line to permit recharging through the pump column. A 1.9 cm diameter pipe was attached to the pump column during installation to facilitate measuring water levels inside the well.

4. *Results of preliminary pump tests* : Before initiating recharge trials with the completed facility, pump tests were conducted to obtain refined data on well and aquifer characteristics. Results of a two-week constant discharge pump test indicated that the specific capacity of the well was about 15.0 m^3/hr/m of drawdown, and that the transmissivity and storage coefficient of aquifer materials were 487 m^2/day and 0.0218 respectively. Additional pump tests showed that the maximum pumping rate of the well was about 113 m^3/hr. Consequently, the maximum recharge rate of the well should not exceed this value in order to permit effective redevelopment after recharge.

5. *Results of recharge trials :* Fourteen short-term recharge trials were conducted in 1967, (a) to obtain preliminary data on the intake characteristics of the well; (b) to compare intake values during recharge through the well casing

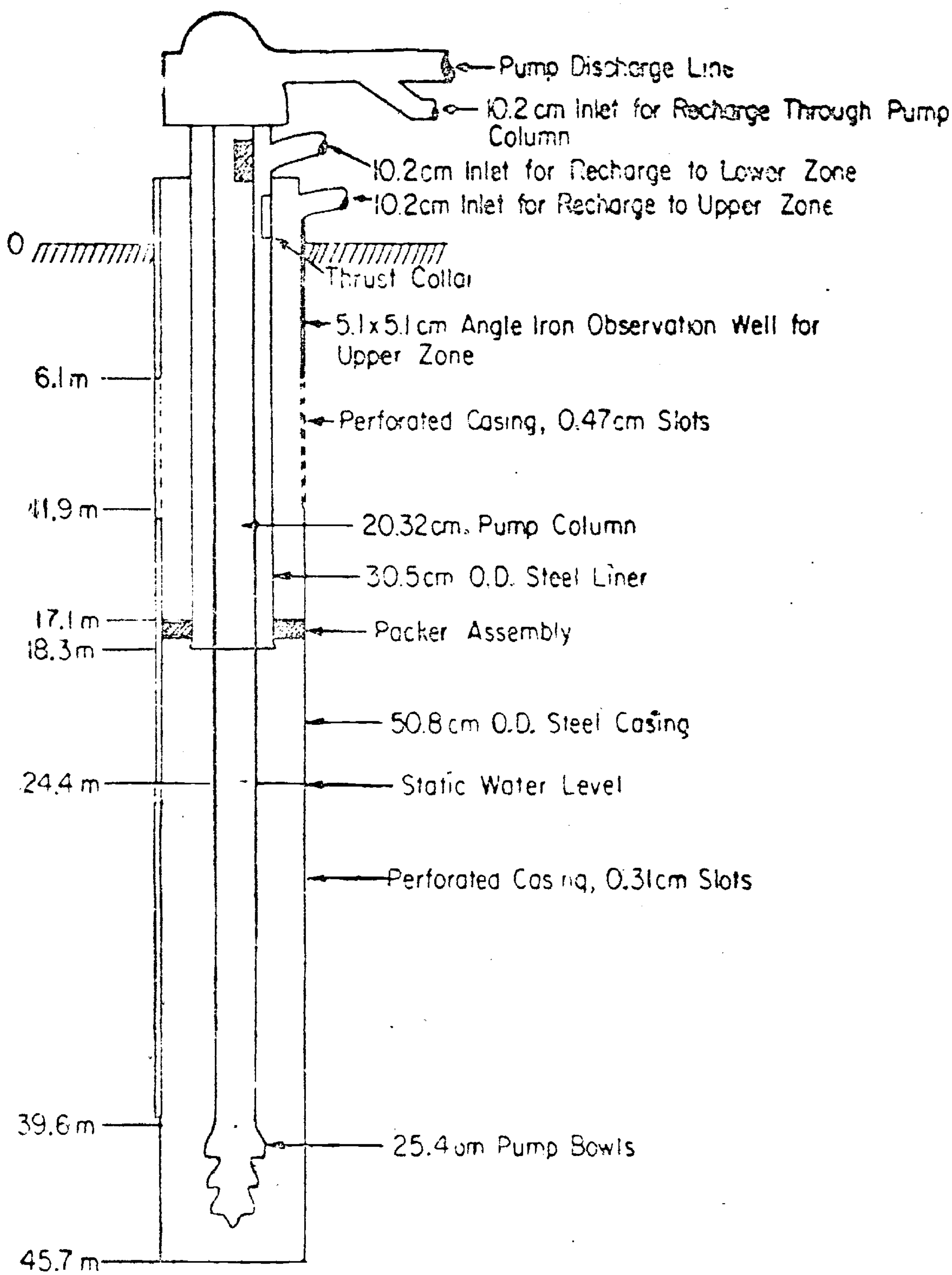

FIGURE 1. DUAL RECHARGE WELL
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with those obtained during recharge through the pump column; (c) to determine head loss across the well casing during recharge; and (d) to determine the effect of recharge on the specific capacity of the well.

Only the lower perforated region was recharged during these trials, effluent being introduced into the well casing for certain trials and through the pump column for others. Care was exercised to maintain a full pipeline throughout each recharge period to minimize air entrainment and the consequent "air binding" of aquifer materials a severe problem in well recharge operations (Sniegocki, 1963). Injection rates and cumulative inflow volumes were metered with a propeller flow meter in the supply line. The rates were held essentially constant for each trial, but varied for different trials. Periodic water level measurements were obtained inside and outside the well casing during recharge. The salinity of the reacharge effluent was monitored at intervals throughout each test to ensure compatability with the salinity of native ground water. The effluent was not chlorinated during these preliminary trials. The well was pumped for a short time after each trial to promote redevelopment of aquifer materials.

The duration of individual recharge trials varied from one hour to 28 hours, and the injection rates ranged from 23 m^3/hr to 102 m^3/hr The maximum and minimum volumes injected during the 14 trials were 2026m^3 and 87 m^3, respectively. The average quality of recharge effluent was slightly better during the trials than the corresponding quality of native ground water; 800 mg/l cf. 1100 mg/l. Specific intake values (i.e., injection rate per incremental rise in water levels above static levels, m^3/hr/m) declined continuously throughout each trial, approaching a minimum of about 11.0 m^3/hr/m. As expected, the specific intake at the well during recharge was less than the corresponding specific capacity during pumping because of hysteresis (Todd, 1959). Recharge did not deleteriously affect the well characteristics, however, because the original specific capacity was recovered during redevelopment. The maximum head loss across the well casing was about 15.2 cm. No apparent differences in specific intake or head loss values were detected between the two recharge methods, i.e., recharging through the well casing or through the pump column.

CONCLUSIONS AND FUTURE PLANS

The results of the preliminary recharge trials show that wells may be effective tools in a water conservation program for the Tucson Basin. The design and construction of individual units must be based on a thorough knowledge of hydrogeologic conditions at the proposed site. For injection into the phreatic zone, operation of the recharge facility should include regular redevelopment periods in order to sustain intake rates and prevent deterioration of the well characteristics.

Future studies using the Water Resources Research Center recharge well will examine the following: (1) The management requirements to sustain intake rates in the phreatic zone during long term recharge operation (i.e., redevelopment requirements, the value of chlorination, etc.); (2) the management requirements to sustain intake rates duriug injection into the upper perforated zone (the sustain intake ratos during injection into the upper perforated zone (the resultant rates and management requirements will be compared with those for injection in the phreatic zone); and (3) the operational requirements to ensure mixing and dilution of recharge effluent with native ground water. Results from these studies will be reported as they become available.

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