Annotated Bibliography on Artificial Recharge of Ground Water Through 1954

By DAVID K. TODD

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ANNOTATED BIBLIOGRAPHY ON ARTIFICIAL RECHARGE OF GROUND WATER THROUGH 1954

By David K. Todd

INTRODUCTION

The increasing use of ground water for industrial, municipal, and irrigation supply in the United States has emphasized the need for recharging the ground water in many areas by artificial means. Although the practice of artificial recharge is not widespread in the eastern half of the United States, it has been important in southern California for water conservation and flood control since about 1895. In Europe many cities have augmented their water supplies by artificial replenishment of heavily pumped aquifers. An increasing interest in artificial recharge is indicated by studies, tests, and research in other parts of the world.

Artificial recharge may be defined for the purpose of this bibliography as the practice of increasing by artificial means the amount of water that enters a ground-water reservoir. Artificial recharge may be divided into direct and indirect methods. Direct methods include water spreading—flooding an area or admitting water into shallow basins, ditches, or furrows; extending the time during which water is recharged from a naturally influent channel; applying excess water for irrigation; recharge through pits and other excavations of moderate depth; and recharge through relatively deep wells and shafts. Indirect methods consist of inducing the movement of water from lakes and streams into underground formations by pumping water from wells, collectors, galleries located near the surface-water sources.

The above classification includes the major methods of artificial recharge. Many operations include more than one method of recharging, and the methods described grade into one another. Each has certain inherent advantages and disadvantages; the selection of methods generally is based on consideration of several of the following factors: climate, topography, soil, geology, water quality, purpose of recharge, quantity of water involved, cost, and land use.

Artificial recharge as a means of water conservation has the distinct advantages of not requiring large and elaborate structures and of utilizing available natural subsurface reservoirs. Economically it compares well, as it must, with other methods of obtaining needed water supplies. Studies of proposed conservation projects in the western United States indicate that in some places large savings could be made by developing integrated surface and subsurface storage. In such systems the size and cost of surface storage and distribution systems can be reduced by supplying artificial recharge to underground reservoirs. Evapotranspirative losses from water stored beneath the ground are usually less than those from surface-storage units. These, together with other demonstrable advantages, suggest that future practice of artificial recharge will not be confined to areas of overdraft and limited ground-water supplies, as is the present general practice.

Rates of artificial recharge vary widely. Much of the current research on the subject is directed toward ascertaining what factors control rates and how these factors operate. Factors such as time, soil, temperature, sunlight, bacteria, vegetation, chemicals, subsurface geology, head of water, water quality, and permeability have been investigated for their effect on recharge rates. Caution is necessary in designing a new artificial-recharge system for a given locality on the basis of rates measured in other localities. A preliminary investigation of the local conditions is advisable rather than an assumption as to expected recharge rates.

This annotated bibliography summarizes available literature pertaining to artificial recharge of ground water. Each reference listed is accompanied by a short abstract designed to provide sufficient material to enable the reader to obtain the important points of the reference without reading the entire paper. For specific information, details, and data, the reader must, of course, turn to the original paper. However, it is the intent of these abstracts to assist him in deciding which papers to investigate.

The selection of papers in this bibliography has emphasized design rather than principles, for an emphasis on principles alone would have necessitated the elimination of many of the papers. Some geologic terms are used in a sense differing from that in accepted scientific usage, but as contributions to the literature on artificial recharge come from a wide variety of sources, such variation in usage is to be expected.

The bibliography is arranged in alphabetical order, by authors. Where several papers are by the same author, references are in chronological order. The material is indexed by method of recharge and area. References have been assembled on a worldwide basis, although most come from the United States. The bibliography covers material up to and including the calendar year 1954. For comparative and analytic purposes, artificial-recharge rates have been converted to common units. Rates of recharge by water spreading are given as feet per day over the wetted area; rates of recharge through wells are reported in cubic feet per second (cfs).

The literature on artificial recharge of ground water is drawn from many fields—civil engineering, geology, hydrology, soil science, and agriculture. In order to keep the bibliography to a practical size, its scope has been carefully limited. Literature on brine disposal through wells, water-flooding methods for secondary oil recovery, and the operation of industrial-waste-disposal pits and wells are excluded, because in these operations the purpose, rates, equipment, water quality, and depths of recharge differ markedly from those in recharge of fresh ground water. Excluded also are papers on infiltration and permeability unless they refer specifically to artificial recharge. In larger references, such as books and reports, only those portions relating to artificial recharge have been abstracted. Other than these specific exclusions, the bibliography covers all the methods previously classed as artificial recharge according to the definition given on page 1.

The foreign literature abstracted comes largely from Germany, Sweden, France, and Great Britain. Only meager information is available from other nations, but to a large extent it is all that exists. In Europe artificial recharge began more than a century ago, and today, particularly in Germany and Sweden, it is a standard procedure for augmenting municipal water supplies. Although actual needs for additional ground-water supplies may be many years away, study and research on possible methods of artificial recharge are already under way in many countries.

The bibliography in its present form is the product of efforts by several organizations and many individuals. It had its beginning several years ago as part of a cooperative research project among the Indiana Department of Conservation, Purdue University, and the U. S. Geological Survey. Representatives of these organizations composed a Committee on Conservation of Ground Water to study the declining water levels in parts of Indiana and to provide information that would be helpful in connection with the recent legislative action of the State in controlling the use of ground water for cooling purposes. On January 14, 1948, the committee appointed a subcommittee composed of Fred H. Klaer, Jr. (Chairman), Frederick W. Greve, and Charles H. Bechert to proceed with the preparation of a synopsis of available data relating to artificial recharge of underground waters. The result was "A preliminary list of references pertaining to artificial recharge of ground water in the United States," by Fred H. Klaer, Jr., William F. Guyton, and the present writer. The list was duplicated for limited distribution by the U. S. Geological Survey on August 18, 1948. After 1948, Mr. Klaer began the task of abstracting references on this list, and copies of those abstracts completed were supplied to the writer. The present bibliography is extended and expanded from the 1948 list, covering additional references and material published since 1948 and including foreign literature.

A few abstracts prepared in final form by others than the writer have been included. These are acknowledged by initials at the end of the abstracts. Initials refer to the following men: *FHK*, Fred H. Klaer, Jr.; *MGM*, M. G. Moore; *NR*, N. Rogers; *GWS*, George W. Steinbruegge; *HPT*, H. P Thielman; *RCV*, Robert C. Vorhis; and *GAW*, George A. Whetstone.

Many individuals furnished references and information that were of great assistance in preparing this bibliography. Valuable help was furnished by district geologists of the U. S. Geological Survey and by many foreign geologists. Specific acknowledgments for substantial contributions are due Harvey O. Banks, Charles H. Bechert, William F. Guyton, Fred H. Klaer, Jr., Dean C. Muckel, Raymond C. Richter, George W. Steinbruegge, Max Suter, Robert C. Vorhis, and personnel of Region 2 of the U. S. Bureau of Reclamation.

The bibliography was prepared under the general direction of A. Nelson Sayre, chief of the Ground Water Branch of the Geological Survey, and under the supervision of Joseph F. Poland, district geologist of the Ground Water Branch for California. Appreciation is expressed to them for their guidance and counsel.

BIBLIOGRAPHY

Achten, A.

1947. A recent example of artificial recharge of an aquifer: La Technique Sanitaire et Municipal (in French), v. 42, p. 76; 1948, abstracted, *in* Am. Water Works Assoc. Jour., v. 40, p. 1139.

The author states that ground water cannot be systematically exploited to the fullest extent without artificial recharge. The town of Ligny, France, pumping 3.3–6.6 cfs, had to discontinue use of underground water in spite of the fact that a substantial supply was available. Artificial recharge, however, raised the water table 30 feet to its original level.

Adamson, J. H., Jr.

1947. Review of ground-water collection and development methods: Am. Water Works Assoc. Jour., v. 39, no. 8, p. 739–746.

Artificial recharge in New York, New Jersey, and California is described briefly.

Allison, L. E.

1947. Effect of micro-organisms on permeability of soil under prolonged submergence: Soil Science, v. 63, p. 439–450.

The permeability of continuously submerged soils usually decreases slightly at first and then increases appreciably as the entrapped air is removed by solution in the zone of percolation. Subsequently, a gradual reduction in permeability occurs until the soil virtually seals up.

Permeability tests made under sterile conditions, to determine the cause of decreased permeability under prolonged submergence, gave no indication of soil-aggregate breakdown due to purely physical causes. The reduction in permeability appears to be due entirely to microbial sealing. The soil pores probably become clogged with the products of cell growth, slimes, or polysaccharides. If any of the observed reduction in permeability was due in part to disintegration of soil aggregates, the dispersion is believed to have been due to biological rather than chemical causes—that is, the attack of micro-organisms on the organic materials that bind soil into aggregates.

Alter, A. J.

1952. Notes on modern Swedish water supply and treatment practices: Am. Water Works Assoc. Jour., v. 44, no. 5, p. 387–391.

Approximately 10 percent of the urban population of Sweden obtains its water supply from artificially recharged ground-water sources. In most installations water is filtered before recharging so that turbid water will not penetrate and clog the pores of the soil. At Sala, where a distance of 500 feet separated the recharge basin and the pumped well, untreated water was applied directly to the natural sand layer. After 35 years the highly colored and turbid water completely penetrated the natural sand layer and the color of the well water began to increase.

The rate of recharge must be carefully regulated, and the flow should be continuous during winter months to prevent freezing. The ideal storage time for recharge water is assumed to be 6 months. The advantages of the Swedish recharge methods are said to be that coagulation and settling of the water pumped from the wells are unnecessary, that biological action in a natural aquifer affords the most suitable means for taste and odor control, and that the recharging process equalizes the temperature fluctuations of surface waters.

American Society of Civil Engineers

1949. Hydrology handbook, Manual of Engineering Practice No. 28: New York, 184 p.

Water spreading and stream-bed percolation are described, on pages 61–62, as a means of increasing ground-water recharge. Areal studies in California and New Mexico are mentioned briefly.

Arnold, C. E.

1949. (and Hedger, H. E., and Rawn, A. M.). Report upon the reclamation of water from sewage and industrial wastes in Los Angeles County, California: Los Angeles County Flood Control District, Los Angeles, California, 159 p.

This is a comprehensive report describing the source, preparation, use, and costs of reclaimed water in Los Angeles County, Calif. Sewage effluent from secondary treatment is recommended for use by recharging into spreading basins to augment ground-water supplies. An average percolation rate of 1.0 foot per day was assumed for proposed spreading operations. It is further assumed that each basin will be operated on a biweekly cycle of being filled, dewatered, dried, and cultivated. Tests showed no evidence of an odor problem.

Appendix C includes a report by Jordan, Koch, and Stone (1949).

Asketh, J. S.

1947. Ranney water collectors in New England: New England Water Works Assoc. Jour., v. 61, no. 4, p. 312–327.

A brief general discussion of Ranney collector wells is presented.

Austen, W.

1939. Physikalische und chemische Beobachtungen bei der Grundwasseranreicherung (Physical and chemical observations during replenishment of ground water): Gas- u. Wasserfach, v. 82, no. 34, p. 606.

In Breslau, Germany, ground water is recharged from ponds filled with water from a river. In field study of ground water in the area, observation wells were located between the pond and a pumping well 130 feet distant. A single application of 225 ppm of sodium chloride was made to the pond. Observations of water level, temperature, chloride, and bacterial count were made on all wells at 8-hour intervals for 80 days. Results indicated that bacteria are removed from the water within a short distance from the pond, that water temperature equals soil temperature at a point about 100 feet from the pond, and that the horizontal flow of water averages about 3 feet per day but varies greatly with soil changes.

1942. Physical, chemical, and bacteriological changes in ground water due to unfiltered surface water; A Yearbook for Water Chemistry and the

Technique of Water Treatment: Deutscher Chemiker Ver., Verlag Chemie, G. m. b. H., v. 15, 368 p.

A review of the development of ground-water supplies for Breslau, Germany, is presented. Seepage ponds recharging the ground water with Ohle River water have been used for many years. Changes in quality of river water and its effect on ground water are discussed in detail.

Avery, S. B., Jr.

1953. Analysis of ground-water lowering adjacent to open water: Am. Soc. Civil Engineers Trans., v. 118, p. 178–208.

This paper presents formulas and graphs for determining in advance well-pumping capacities required to maintain drawdown at particular elevations adjacent to open bodies of water. To simplify the analysis, well installations have been considered to be circular.

Babcock, H. M.

1942. (and Cushing, E. M.). Recharge to ground water from floods in a typical desert wash, Pinal County, Arizona: Am. Geophys. Union Trans., v. 23, pt. 1, p. 49–56.

An investigation of recharge to ground water from Queen Creek, Pinal County, Ariz., was carried out to determine the practicability of water-spreading operations to increase natural recharge. The stream is a typical dry desert wash and subject to quick floods. During 1940 and 1941 a total of 17 flood flows were measured to determine the recharge rates. Values over the wetted area ranged from 0.14 to 2.09 feet per day for the different floods and averaged 1.08 feet per day. Owing to unusually heavy rains early in 1941, the stream flowed continuously for 3 months. Seepage was measured during this period and averaged more than 4 feet per day. The marked difference between this rate and the flood rate is attributed to the fact that the flood waters were silt-laden, while the other flows were comparatively clear.

A third set of measurements included the rate of decline of pools of water remaining in the channel after floods. Rates ranged from 0.16 to 2.76 feet per day, and the initial rates averaged 0.91 foot per day.

Bacon V. W. *See* Stone, R. V., 1952b.

Baker, D. M.

1930. (and Conkling, H.). Water supply and utilization: New York, John Wiley and Sons, 495 p.

A section of this book describes briefly (p. 362–365) methods of artificial recharge and summarizes observed percolation rates in southern California streams.

Balmer, G. G. *See* Glover, R. E., 1954.

Banks, H. O.

1953a. Problems involved in the utilization of ground-water basins as storage reservoirs: Assoc. Western State Engineers, 26th Annual Proc., p. 91–105.

The Los Angeles County Flood Control District conducted a series of experiments at Manhattan Beach, Calif., from April 1950 to February 1951 to determine rate of injection of water into a confined aquifer. An abandoned

well was used for the injection. Check wells surrounded it. Between May 16 and October 13, 1950, 325 acre-feet were injected at rates varying from 0.5 to 2.3 cfs. At first it was difficult to maintain the rate of injection due to formation of bacterial slime, air entrainment, deposition of suspended solids, deposition of calcium carbonate, and base exchange reactions. By excluding air and chlorinating the water, most of these difficulties were overcome. During a 29-day period in which liquid chlorine was added to the water, the injection rate dropped from 2.38 cfs to 1.73 cfs. A stabilized condition was not reached before the test had to be terminated. Fresh water from the Colorado River was used for injection but amount of pretreatment, if any, is not indicated. *GWS*

1953b. Utilization of underground storage reservoirs: Am. Soc. Civil Engineers Trans., v. 118, p. 220–234.

Two spreading areas, of 75- and 145-cfs capacity, are located in Ventura County, Calif. Two methods of distributing new ground water to the coastal plain of Ventura County to prevent further sea-water intrusion are injection through wells into confined aquifers and injection through wells to form a ground-water ridge along the coast.

1953c. (and Richter, R. C.). Sea-water intrusion into ground-water basins bordering the California coast and inland bays: Am. Geophys. Union Trans., v. 34, no. 4, p. 575–582.

Direct recharge of overdrawn aquifers and the maintenance of a fresh-water ridge above sea level along the coast are possible methods for controlling sea-water intrusion into coastal aquifers. Either water spreading or injection wells can be used. Use of reclaimed water may be feasible. An experimental field study of a pressure ridge fed by a line of injection wells is briefly described.

1954. (and Richter, R. C., Coe, J. J., McPartland, J. W., and Kretsinger, R.) Artificial recharge in California: California Div. Water Resources (mimeo.), 41 p.

This paper is a progress report on a comprehensive investigation of artificial recharge of ground water in California being conducted by the California Division of Water Resources. A complete inventory of artificial recharge projects is being made to determine the extent of recharge, to obtain design criteria and cost data, and to obtain information on operation and maintenance problems.

Recharge activities in California date from 1895, when flood waters of San Antonio Creek were conserved by spreading the water on its alluvial cone. In the present investigation 87 artificial-recharge projects have been studied. For each project the name of the project, the responsible agency, the source of water, method of recharge, total and maximum annual recharge amounts, and reported costs are shown in tables. Artificial recharge activities are concentrated largely in the Santa Clara Valley south of San Francisco Bay, in the South San Joaquin Valley, and in southern California. Other data presented show reported amounts of water artificially recharged annually in each ground-water basin since 1941.

The most common method of artificial recharge is through use of basins. Spreading in ditches and furrows and in natural stream channels is practiced to a lesser extent, and abandoned gravel pits have been used to a limited degree.

Brief descriptions are included of unusual projects in Sierra Madre, Los Angeles County, and Orange County; and of proposed projects in Monterey County, Santa Barbara County, Ventura County, and Los Angeles County. Operation and maintenance problems of various methods in different locations are outlined. Experimental investigations and research by the Los Angeles County Flood Control District, the University of California, California State Water Resources Board, Soil Conservation Service, and Bureau of Reclamation are summarized.

The following factors must be considered in the location, design, and operation of artificial recharge projects: proper location with respect to the geology of the area, soil textures in the recharge area and aquifer characteristics, the pattern of draft on the basin, acquisition of sufficient lands and rights-of-way and cost thereof, construction and maintenance of works for diversion of water from streams, silt control, maintenance of percolation rates, necessity for regulating surface storage flows for later release, capacity of the ground-water basin, prevention of nuisance, protection of public health in the recharge of waste waters, quality of recharge waters, degree and cost of necessary prior treatment, rodent control, and algae and weed control.

Barksdale, H. C.

1943. (and others). The ground-water supplies of Middlesex County, New Jersey: New Jersey Water Policy Comm. Spec. Rept. 8, 160 p.

Artificial recharge of certain aquifers at Perth Amboy and Duhernal, N. J., is discussed.

1946. (and DeBuchananne, G. D.). Artificial recharge of productive ground-water aquifers in New Jersey: Econ. Geology, v. 41, no. 7, p. 726–737.

Artificial recharge by water spreading is practiced in several places in New Jersey. At the Perth Amboy Water Works recharge is through shallow basins and canals to a body of sand of Cretaceous age 80 feet thick. Wells drilled in this sand have been supplying the Water Works for more than 40 years. Recharge rates were measured at 0.01 to 0.38 foot per day, the higher rate being considered more representative.

A few miles to the southwest at Duhernal, a low auxiliary dam was constructed to increase the ground-water recharge by enlarging the water-contact area. The aquifer is the same sand as that exposed at the Perth Amboy works. Results have been satisfactory although no quantitative measurements have been made.

The Princeton Water Co. has pumped water from Stony Brook for more than 20 years for spreading near its wells. The recharge area is covered with shrubs and other vegetation, and the average rate is estimated at 0.08 foot per day. The aquifer in this area is a jointed and fissured, relatively impermeable conglomerate sandstone and shale.

At Lake Mohawk, water is recharged into glacial sand and gravel of a preglacial valley by an underground trench 3 feet wide, 15 feet deep, and 260 feet long. The bottom 6-to-7 feet is filled with 2-inch gravel on top of which lies a slab of concrete, and the remainder is filled with clay to prevent surface percolation. A pipe from the lake recharges the gravel, and a group of wells is located a short distance from the trench. The installation has overcome the deficient aquifer storage capacity, and a continuous water supply is now available from the wells.

Since 1937 the city of East Orange has operated several water-spreading basins. The largest of these has an area of 11 or 12 acres. Initially the re-

charge rate measured 0.52 foot per day, but this decreased by 1945 to 0.40 foot per day. It is believed that by occasionally dredging or scarifying the bottom of the basin, its efficiency can be maintained at about the present rate. The aquifers in this area are glacial valley-fill deposits of sand and gravel.

1949. Depletion of ground water in New Jersey: Am. Water Works Assoc. Jour., v. 41, no. 6, p. 511–515.

Artificial recharge is being practiced at Perth Amboy, Duhernal, East Orange, and Newark, N. J.

Barnes, A. S. L.

1948. Conservation and water supply: Water and Sewage, v. 86, no. 4, p. 70–74, 97–98.

Moose Jaw is the only city in Canada practicing water spreading on an extensive scale. Water is pumped from the Saskatchewan River to a high point from which it flows 78 miles into a large sand area. Water is extracted in the sand area by 260 Griffin sandpoints sunk to a depth of 25 feet and is pumped into the main supply line for use.

Water spreading in Ontario as a means of water conservation and flood control is recommended.

Barnes, H.

1945. Memorandum on ground water replenishment in Madera Irrigation District in 1944 through utilization of natural stream channels: Madera Irrig. Dis. (mimeo.), Madera, Calif., 17 p.

Water was released into the channels of Cottonwood Creek and Fresno River in the last half of 1944 for the purpose of ground-water recharge. A total of over 35,000 acre-feet of water was recharged. Ground-water levels showed an average rise of over 3.5 feet over an area of 85,000 acres, indicating the practicability of the method in this area.

Barrows, G.

1913. (and Wills, L. J.). Records of London wells: England and Wales Geol. Survey Mem., London, 215 p.

The use of "dumb" wells for recharging excess surface water into sand and chalk aquifers in the London area is suggested (p. 13–14). Such wells should be located where sufficient water is available, where the water is clear or can be cleared, and where a steep gradient in the water table exists so that the recharged water will flow toward the area of partial depletion. Since 1890 excess winter flows of the Lea River have been recharged into galleries in the chalk. This has had the desired effect of keeping the water table high.

Bartz, P. M.

1949. Physical aspects of ground water use in the upper San Joaquin Valley: Berkeley, California Univ. Doctoral Dissert., 234 p.

In a detailed investigation of the upper San Joaquin Valley ground-water basin in California, it was found that canal conveyance losses, excess irrigation, and percolation from stream beds contribute approximately 55 percent, 30 percent, and 15 percent, respectively, of total recharge. Direct penetration of rainfall is shown to be a negligible factor.

Artificial recharge can be conducted by four methods: excess irrigation, percolation from canals and laternals, diversion of water into stream channels

to increase seepage losses, and use of spreading basins, pits, and shafts. The first two methods will furnish only a limited amount of recharge because of problems of waterlogging and alkali accumulation and of extensive sheets of relatively impervious hardpan. The third method promises to be initially the most effective, while the fourth method requires further study to determine continued recharge rates. An experimental program for this purpose is now underway.

Baumann, P.

1952. Ground-water movement controlled by spreading: Am. Soc. Civil Engineers Trans., v. 117, p. 1024–1074.

A mathematical analysis of two- and three-dimensional flow in porous media as applied to water-spreading and recharge-well systems is presented. Results are compared with model tests of two-dimensional flow.

1953. Experiments with fresh-water barrier to prevent sea-water intrusion: Am. Water Works Assoc. Jour., v. 45, no. 5, p. 521–534.

An artificial recharge test program by Los Angeles County Flood Control District, Calif., for control of sea-water intrusion is described. Spreading plots constructed at Redondo Beach and El Segundo had an area of 1 acre each and a water depth of about 2 feet. At El Segundo 25 seepage pits 30 inches in diameter were dug through a subsurface layer of sandy loam of low permeability and terminated in dune sand. These were filled with uniform clean pea gravel. Recharge waters were treated with either chlorine, calcium hypochlorite, or copper sulfate to prevent formation of bacterial slime and algae. Tests showed that spreading rates of 4 feet per day could be maintained. Recharged water became perched on less permeable clay lenses.

Tests were conducted on a recharge well at Manhattan Beach. The well is a 16-inch cased well 350 feet deep with 32 feet of standard slot perforations in the most permeable zone starting 230 feet below ground surface. Water was injected for 5 months in 1950. Recharge rates were reduced by the oxygen content of the water which stimulated growth of micro-organisms. This problem was solved by deaeration and a dosage of 10 ppm of chlorine. The tests showed that with proper treatment a recharge rate of 2 cfs could have been maintained at maximum head, and that the rise of the pressure mound around the well in the confined aquifer was in direct proportion to the injection rate.

Idealized recharge mounds around a well are shown for level and inclined water tables. Future tests are described in which a line of recharge wells would be located parallel to the coast.

Beardslee, C. G.

1942a. Salt-water barrier at Cooke: Western Construction News, v. 17, no. 2, p. 53–55.

This article describes construction of an impermeable weir near the mouth of the Santa Ynez River, Calif., to prevent sea-water intrusion and to conserve fresh-water supplies by ponding surface and subsurface flows in dry seasons, and by increasing ground-water recharge by raising water levels upstream.

1942b. Underground storage for floods assures army camp water supply: Eng. News-Rec., v. 128, no. 11, p. 406–407.

Near the mouth of the Santa Ynez River, Calif., an impervious earth barrier is being constructed to retain and spread flood waters formerly wasted to the

sea. The increased ground water will provide an adequate water supply for nearby Camp Cooke.

Bechert, C. H.

1949. (and others). Current developments in ground water law: Am. Water Works Assoc. Jour., v. 41, no. 11, p. 1002–1012.

Recent legislation pertaining to artificial recharge of ground water for the states of Indiana, New Jersey, New York, and Ohio is described.

Beebe-Thompson, A.

1950. Recharging London's water basin: Times Industry Rev., v. 4, no. 46, p. 20–22, 25.

This article advocates that serious consideration be given to recharging Thames River water into chalk aquifers to augment the dwindling ground-water supply of the Greater London area. It is possible that recharging the chalk may introduce pollution; however, modern methods of sterilization should insure absolute water safety. Recharging and subsurface storage can be expected to compare favorably with direct treatment and surface storage of river water.

Bennett, L. G.

1947. Memorandum on Merritt and Ochletree recharge well: U. S. Bur. Reclamation, Modesto, Calif., 3 p.

Operation of a recharge well near Madera, Calif., during 1946 is described. In a 6-month period the average recharge rate was 1.93 cfs. Flows into the well fluctuated widely. The original recharge capacity was 3.5 cfs. The success of this recharge well has been attributed to the fact that a pumped irrigation well is located nearby. Two other recharge wells at a greater distance have not been equally successful.

Bennison, E. W.

1947. Ground water: St. Paul, Minn., Edward E. Johnson Co., 509 p.

Water spreading and recharge wells are described (p. 481–496). Spreading grounds in California, New Jersey, and Iowa are discussed. The extensive well-recharge program on Long Island and the wartime emergency recharging at Louisville are explained.

1949. Replenishment of ground-water supplies: Am. Water Works Assoc. Jour., v. 41, no. 2, p. 207–208.

A brief general discussion of artificial recharge is given.

Biemond, C.

1940. Rapport-1940 inzake de watervoorziening van Amsterdam (Report-1940 on the water supply of Amsterdam): Amsterdam, Netherlands, Stadsdrukkerij.

Details of a proposal to increase the water supply of Amsterdam, Netherlands, by recharging dune areas with river water are presented.

Blaney, H. F.

1936. General review—symposium on contribution to ground-water supplies: Am. Geophys. Union Trans., v. 17, pt. 2, p. 456–458.

In discussing economic limits of conservation of floodwater by spreading, it is indicated that artificial spreading is beneficial and that ground-water

storage with limited surface storage is generally more economical than surface storage only. Permanent diversion structures are essential for controlled spreading of floodwater. Complete conservation of floodwater is uneconomical. Spreading works do not provide flood protection when large floods occur.

Bliss, E. S.

1950. (and Johnson, C. E., and Schiff, L.). Report on cooperative water-spreading study with emphasis on laboratory phases, August 1948–December 1950: U. S. Soil Conserv. Service, 150 p.

The rapid decline in the rate at which fine-textured soils will take water seems to be associated primarily with microbial activity. Laboratory studies have shown that for certain soils infiltration rates can be maintained with a sterile system. Vegetative treatments, including the growth of stands of Bermuda grass and Paragrass, have increased infiltration rates. Ponds in which cotton gin trash has been added to the soil have taken 14 to 16 feet of water per day, although normal rates are only 3 to 4 feet per day. The trash, under proper management, promotes increased aggregation, improved structure, and larger pores. Management includes an incubation period for decomposition, a drying period for aggregation, and finally a running period in which increased infiltration occurs. Experiments show that an incubation period of at least 8 weeks of continuous flooding is necessary to improve rates. Differences in numbers of micro-organisms in water samples from field ponds seemed to have little effect on infiltration rates. A study of surface crusts revealed high carbonate and organic matter contents and apparently better aggregation than in the soil just below. Good correlation has generally been found between organic matter and infiltration rate. No definite relationships were found between conductivity and pH and infiltration rates. All treatments that have benefited infiltration have also reduced volume weight of the surface few inches. Attempts to relate the amount of larger pores to infiltration rates were only partially successful.

The significance of subsurface lateral flow as it affects the infiltration rate in an area has received study. A theoretical opportunity ratio for lateral movement has been developed based on pond area-circumference considerations. A moisture study to a depth of 20 feet in the vicinity of concentric ponds during a run indicated that a saturated cone extends outward and downward at a 45° angle for five feet, then more or less vertically downward.

1952. (and Johnson, C. E.). Some factors involved in ground-water replenishment: Am. Geophys. Union Trans., v. 33, no. 4, p. 547–558.

When water is spread on relatively fine-textured soils a fairly rapid decline in water-intake rate is observed. This decline appears to be associated with microbial activity as well as with other factors that affect infiltration. In laboratory-percolation studies high rates can be maintained as long as the system is kept sterile.

Experiments on field ponds showed that relatively high intake rates can be obtained and maintained for longer than normal periods on spreading areas where dense stands of Bermuda grass have been grown or where there has been proper management of organic materials incorporated in the surface soil. Only limited investigations have been made of reasons for improved water intake in grassed-over areas. Improved intake rates through use of organic residues apparently are due to microbial activity. This activity seems to result ultimately in improved aggregation, stability of structure, and larger

pores. Management of organic residues include decomposition, or "incubation," and drying before benefits are achieved.

Laboratory studies using cotton-gin-trash mulch over disturbed soil in small percolation tubes showed 8 weeks of continuous flooding was more effective for incubation than 2 or 4 weeks. The longer period of incubation and subsequent drying increased percolation rates over that of untreated controls, while incubation by intermittent irrigation for as long as 16 weeks did not.

Use of water extracts of gin trash on soils greatly depressed intake rates during an incubation run and had a continued depressive effect on subsequent tap-water run. When a detergent was used at 0.01-percent concentration, it quickly depressed percolation rates. Counts of micro-organisms made during and after these runs showed large increases in total numbers, which may have caused the decreased rates.

Physical measurements of surface soils in organic-residue-treated ponds show large increases in total and noncapillary porosity over untreated soils. Comparison of intake rates on such ponds indicates that other factors, in addition to surface porosity, operate in controlling rates.

Hydrogen-ion concentration and conductivity studies of the water in test ponds show that these factors fluctuate widely during test runs, but that the fluctuations do not appear to affect the water intake.

Bogart, C. L. *See* Flinn, A. D., 1927.

Bogart, E. L.

1934. Water problems in southern California: Illinois Univ. Social Sci. Studies, v. 19, no. 4, p. 44–48.

The first water spreading practiced in southern California was done by the Irvine Ranch Company from Santiago Creek in 1896. A history and short description of several water-spreading projects in northern California are given. Studies have indicated a rate of absorption of 8 feet per day by flooding and a rate of 2 feet per day over the total area of which 25 percent is wetted by ditches and other means. Undisturbed cover and flow across spreading areas are recommended. E. W. Hilgard is said to have been the first to suggest in scientific literature the possibility of artificial replenishment of ground-water supplies. *FHK*

Boswell, P. G. H.

1954. Artificial replenishment of underground water resources in the London Basin: Water and Water Eng., v. 58, no. 700, p. 253–257.

This article discusses possible recharge projects in the London Basin and the subjects that need study before such projects can be undertaken. *RCV*

Bowerman, F. R. *See* Rawn, A. M., 1953.

Brashears, M. L., Jr. *See also* Leggette, R. M., 1938.

1941. Ground-water temperature on Long Island, New York, as affected by recharge of warm water: Econ. Geology, v. 36, no. 8, p. 811–828.

Ground water used for air conditioning in western Long Island, N. Y., is returned, by law, to the ground. In the 1940 air-conditioning season 142 recharge wells were operating at an average rate of 0.33 cfs per well. The temperature of the recharged water ranges from 2° to 20° F higher than the temperature of the water pumped from the ground. Observations by the U. S.

Geological Survey since 1936 in about 350 wells indicate that the return of the warm water has caused a rise of water temperature as great as 20° F in the centers of some recharge localities. A gradual rise of ground-water temperature has occurred over a considerable part of western Long Island.

1946. Artificial recharge of ground water on Long Island, New York: Econ. Geology, v. 41, no. 5, p. 503–516.

Since 1933 the New York State Water Power and Control Commission has required that water pumped from new cooling and air-conditioning wells be returned to the aquifer from which it is withdrawn. On Long Island, aquifers are glacial outwash gravels which overlie Cretaceous sands in some areas and pre-Cambrian schist in other areas. The policy on recharge has resulted in a number of large recharge basins and recharge wells. In the summer of 1944 more than 200 recharge wells were operating at an average recharge rate of about 0.46 cfs per well. Recharge wells with capacities as high as 2.2 cfs have been successfully constructed.

The temperature of recharged cooling water ranges from 2° to 20° F higher than that of the water pumped from the ground. This has raised ground-water temperatures appreciably in recharge centers, but where wells are not closely spaced or are separated by impervious layers, there has been no serious rise in temperature.

In Nassau County 11 seepage basins, ranging in area from 1 to 9 acres and having a total area of 40 acres, have been established to recharge storm-sewer runoff. Records indicate the average recharge rate to be about 1.5 feet per day, and to be somewhat higher immediately after the bottoms of the basins have been scarified.

Long Island recharge wells are classed as "dry" and "wet" types depending upon whether the well ends above or below the water table. About 75 percent of the wells are of the wet type, and these have generally proved most successful. The dry-type wells are usually finished with a section of perforated well casing, whereas wet-type wells are generally equipped with standard well screen. Because of this factor and because they are shallower in depth, the dry-type wells are less expensive to construct. The disadvantages of the dry-type well include excessive clogging, which results from air-water contact of the recharged water, and lack of reconditioning by redevelopment methods. The presence of even small quantities of silt in recharge water may cause serious clogging of screen openings. If recharge and supply wells must be located within short distances of each other, the maximum possible separation between the two well screens should be obtained to minimize the connection between them.

1953. Recharging ground-water reservoirs with wells and basins: Mining Eng., v. 5, p. 1029–1932.

Presents a general review of artificial recharge by means of wells. In contrast to spreading grounds, recharge wells occupy a minimum area, require water of low turbidity and silt content, and can recharge aquifers that do not extend to the ground surface. Mixing of recharged and pumped waters below ground can be avoided by locating wells at different depths, because, typically, horizontal permeabilities exceed vertical ones.

Recharge well operations at Louisville, Ky., Binghamton, N. Y., Canton, Ohio, Long Island, N. Y., and El Paso, Tex., are described.

Brater, E. F. *See* Ferris, J. G., 1949.

Brumley, D. J.

1949. Atomic energy town of Richland, Washington, grows from 250 to 25,000 population: Civil Eng., v. 19, no. 6, p. 391–395.

In the spring of 1948 the water supply of Richland, Wash., was expanded by developing two idle gravel pits as recharging basins, using water from the Yakima and Columbia Rivers. Collecting wells, 50 to 70 feet deep, surround the basins and pump the recharged water. Water is chlorinated and pumped into the supply lines.

Bruns, H. *See* Konig, A., 1930.

Bryan, L. L. *See* Stearns, H. T., 1939.

Bücher, C.

1928. Die Wiesbadener Wassergewinnungsanlagen in Schierstein a. Rhein unter besonderer Berücksichtigung der in 1921 bis 1924 durchgefuhrten Um- und Erganzungsbauten zur Erzeugung künstlichen Grundwassers (The Wiesbaden waterworks in Schierstein on the Rhine with special reference to the works constructed in 1921-1924 for obtaining artificial ground water): Gas- u. Wasserfach, v. 71, no. 24, p. 577–581, no. 25, p. 608-612, no. 26, p. 631-635.

The expansion of the water-supply system for Wiesbaden, Germany, during the period 1921-24 is described. Water is pumped from the Rhine, passed through sedimentation basins and then into infiltration basins. The recharged water is then pumped by a row of wells inland from and paralleling the river and the recharge basins. The geology and hydrology of the area are described together with details of the waterworks installation.

Burdick, C. B. *See also* Meinzer, O. E., 1942.

1924. Infiltration galleries at the Des Moines, Iowa, water works: New England Water Works Assoc. Jour., v. 38, no. 3, p. 203–218.

The water supply for Des Moines, Iowa, is obtained from a 2-mile horizontal collecting gallery located in porous strata paralleling the Raccoon River. In order to increase the supply to the gallery during dry years water has been pumped from the river and spread on the land above and more than 100 feet from the gallery. Gallery water levels can be brought up to any desired level by controlling the amount spread upon the land. The flooding produced no noticeable change in water quality. The soil beneath the spreading area is sandy, and interspersed with pockets of gumbo. During 1922 water was applied to a land area of 13 acres continuously for 4 months at an average rate of 1.18 feet per day.

1946. Des Moines infiltration system was developed methodically: Water Works Eng., v. 99, no. 9, p. 461–463, 534, 536.

The use of a collecting gallery and water-flooding basins for water supply from ground water at Des Moines, Iowa, is described. Infiltration rates from the river bed equal about 0.67 foot per day under low-flow conditions. The flooding basins are given no special preparation. The water passes downward through 5 to 15 feet of clay silt into the underlying gravel stratum from whence it passes to the gallery. Recharge rates vary widely but approximate 1.5 feet per day. Beds are cleaned at intervals of one to three years by scraping off an inch or so of material with a bulldozer and adding it to the side embankments.

During winter, operations continue normally and water is recharged beneath the ice. Frozen ground is thawed by application of river water. Flooding basins are located 20 to 100 feet from the gallery to insure sanitary safety. No differences in water quality have been observed between river-bed infiltration and land flooding.

Burgess, P.

1911. Some features of design of infiltration systems: Eng. Rec., v. 63, no. 5, p. 136–137.

Some factors affecting the performance of a stream bed infiltration system are described.

Burt, E. M. *See* Ferris, J. G., 1954.

Bush, A. F.

1954. (and Mulford, S. F.). Studies of waste water reclamation and utilization: California Water Pollution Control Board Pub., No. 9, 82 p.

This report covers aspects of water reclamation, including recharging. About one million acre-feet of water are available for reuse in California. Chemical analyses of ground water near recharge locations indicate no appreciable change in water quality. Field samples taken during spreading reveal that soil was saturated to less than 50 percent of capacity. The distance contamination and pollution will travel in water through soils appears to be a function of the percolation rate. After a few days of continuous operation, the percolation rate for sewage waste water drops to a small fraction of the initial rate. Percolation rates are a function of hydraulic head, viscosity, and permeability of the soil layers. The latter is influenced by soil texture, structure, and aggregation; cultivation; soil profile; biologic growths; colloidal activity and ion exchange; degree of saturation, water quality, and possibly other factors. Evaporation and transpiration losses during percolation increase the dissolved mineral content of water. Observed initial field percolation rates appear to be related to the measured laboratory disturbed-soil permeability tests.

Butler, R. G.

1954. (and Orlob, G. T., and McGauhey, P. H.). Underground movement of bacterial and chemical pollutants: Am. Water Works Assoc. Jour., v. 46, no. 2, p. 97–111.

By means of spreading basins, lysimeters, and a recharge well, underground pollution travel was studied. Information was obtained on bacterial removal as a function of soil type, and distance and rate of travel of pollution.

Cady, R. C.

1941. Effect upon ground-water levels of proposed surface-water storage in Flathead Lake, Montana: U. S. Geol. Survey Water-Supply Paper 849–B, p. 59–81.

A graphical analysis is made of proposed regulated higher stages of Flathead Lake on the adjacent ground-water table. It is shown that the increased recharge will raise the water table, but only by small amounts and in limited areas.

California Department of Public Health

1939. Drainage into wells disapproved: Weekly Bull., v. 18, no. 17, p. 66.

The California State Board of Public Health states that disposal of road and land drainage into wells can contaminate domestic water supplies; therefore, the practice is disapproved.

California Division Eng. and Irrig.

1928. Santa Ana investigation—Flood control and conservation: Bull. 19, 357 p.

There are 14 areas in the Santa Ana River basin, California, where water is spread for ground-water recharge. The total capacity of these works is estimated at 200,000 acre-feet per season. The layout, area, construction and capacity of each area is briefly described and illustrated.

Measurements of recharge rates from certain areas have been collected. These are tabulated by area and type of material below.

Area	Material	Recharge rate (feet per day)
San Antonio River, Upland	Gravel and sand	2.8
Santa Ana River, Yorba	Sand	1.8
Santa Ana River cone	Boulders, gravel, and sand	6.8
San Gabriel River	Boulders, gravel, and sand	1.8
San Gabriel River	Small boulders, gravel, and sand	3.0
San Gabriel River	Gravel and sand	4.5
San Gabriel River	Small gravel and sand	9.5
San Francisquito Creek	Gravel and sand	4.5
San Francisquito Creek	Sand	9.6
San Francisquito Creek	Sand	8.2

California Division Water Resources

1930. Santa Ana River Basin: Bull. 31, 73 p.

As part of a comprehensive plan for flood control and conservation of waste water in Santa Ana River basin, Calif., several spreading works would be established to recharge floodwater. Plans call for spreading works on the alluvial cones of Cucamonga Creek, Deer and Day Creek, Lytle Creek, Santa Ana River, and Mill Creek.

1933a. Santa Clara investigation: Bull. 42, 265 p.

Measurements of stream-channel percolation rates were conducted early in 1932 on 16 streams in Santa Clara Valley, Santa Clara County, Calif. As applied to wetted areas, the median observed minimum rate was 1.03 feet per day, and the median observed maximum rate was 4.16 feet per day. Rates ranging from 0.12 to 23.9 feet per day were observed.

1933b. Ventura County investigation: Bull. 46, 244 p.

Graphs of stream percolation in relation to streamflow are presented for reaches of Santa Clara River, Piru Creek, Hopper Creek, and Sespe Creek in Ventura County, Calif.

Two offstream spreading works have been successfully operated for recharging surface waters in the Santa Clara River valley. The area near Piru has a capacity of 80 cfs, and that near Montalvo, 45 cfs. No diversions are made during floods because of the high silt content, and no permanent diversion works have been installed.

As part of an investigation for complete utilization of Ventura County waters, spreading works were recommended near Piru, Saticoy, and in the Ventura River valley. Recharge rates in the Piru area are reported to be 4.5 feet per day, and in the Saticoy area, 7.4 feet per day. Cost estimates and detailed descriptions of proposed spreading works are given.

1950. Sea-water intrusion into ground-water basins bordering the California coast and inland bays: Water Pollution Invest. Rept. 1, 23 p.

Of five proposed methods for controlling sea-water intrusion, two involve artificial recharge. These include direct recharge by spreading and(or) injecting wells to maintain ground-water levels at or above sea level and maintenance of a fresh-water ridge above sea level along the coast by spreading and(or) recharge wells.

1951. Proposed investigational work for control and prevention of sea-water intrusion into ground-water basins: 33 p.

Artificial recharge by spreading and injection wells for controlling sea-water intrusion is discussed. Studies at Los Angeles and at the University of California, in Berkeley, are reviewed and a proposed field and laboratory investigational program is outlined.

California Water Resources Board.

1953. Ventura County investigation: Bull. 12, 490 p.

This bulletin includes a brief description of spreading grounds in Ventura County, Calif., together with tabulation of annual diversions to spreading grounds for period 1936–51.

Campbell, J. D.

1946. Drainage no problem: Mil. Engineer, v. 38, no. 244, p. 56–59.

Various examples of natural and artificial drainage into the porous lava formations on the Hawaiian Islands are described.

Cannard, R. E. *See* Walter E., 1945.

Cannon, G.

1954. Refilling our wells: Atlantic Monthly, v. 194, no. 2, p. 46–49.

This is a popular article on artificial recharge of ground water, stressing the need for an expanded program to provide for future water supply. On the King Ranch in Texas water is stored in a 1,500-acre lake, filtered to remove silt, and recharged through a well.

Briefly described are other recharge efforts on Long Island, N. Y.; near Cincinnati, Ohio; at Dayton, Ohio; at Canton, Ohio; at Williamsburg, Va.; in California; and in the Grand Prairie region of Arkansas.

Cederstrom, D. J.

1947. Artificial recharge of a brackish water well: Commonwealth, Virginia Chamber Commerce, Richmond, v. 14, no. 12, p. 31, 71–73.

Experimental recharging of a brackish water well (chloride content 340 ppm) at Camp Peary near Williamsburg, Va., is described. The well is 472 feet deep and 8 inches in diameter, and has Cook 40-slot screen placed opposite medium-textured sand at 430–440 feet and 450–475 feet below surface. The well yielded 0.68 cfs with a drawdown of 62 feet. The water level in the well stood 70 feet below surface when recharging was commenced so that it was possible to build up a considerable head in the well. Operations were begun on April

4, 1946, and a recharge rate of 0.39 cfs was soon reached. This decreased gradually to 0.31 cfs by May 17, at which time water began flowing out of the top of the casing. Water levels in nearby wells showed that recharge was not being retarded by high artesian pressure, but rather by clogging in the well itself. The well was pumped for 3 minutes in an effort to clear the well. The initial water discharged was fiery red but cleared by the end of the period, indicating that iron rust from delivery mains had collected on the well screen. Afterward the recharge rate was only temporarily increased, leading to the conclusion that packing of sand grains around the well screen was the primary cause of the reduced recharge rate. Recharge operations were suspended after 12 weeks when a total of 52 acre-feet had been recharged.

The well was pumped thereafter for about 3 weeks. This period of pumping was followed by 10 days of no pumpage, and a second pumping period of 7 weeks. Discharge began at 0.50 cfs and increased to 0.59 cfs by the end of the first pumping period. The latter rate was continued throughout the second period. During the first period the chloride content increased from 10-12 ppm to 20 ppm, while in the second period chloride increased steadily up to 220 ppm when a total volume equal to that recharged had been pumped.

About 50 percent of the recharged volume was uncontaminated when pumped out. Some clogging of the well is to be expected, except where the sediments are coarse grained and where the well was highly developed when constructed. Foreign materials from mains should be prevented from entering the well. Restoring the permeability of a clogged well is difficult—surging or the use of several wells may be necessary. An observation well near the recharge well is of considerable value for indicating the extent of recharge and for determining whether any decrease in the rate of recharge is due to clogging or the building up of head in the area.

1954. (and Trainer, F. W.). Artificial recharge of water-bearing beds in Anchorage: U. S. Geol. Survey open-file report (paper presented at the Alaska Science Conference, Anchorage, Alaska, Sept. 8, 1954).

In the spring and summer of 1954 the Ground Water Branch of the U. S. Geological Survey drilled a test well near Ship Creek at Anchorage, Alaska. Water from shallow gravels adjacent to the creek was permitted to flow into the well and pass downward and outward into deeper formations. The test was designed to show whether the excess flow of Ship Creek might be stored underground each year and drawn upon later in periods of low flow.

The mechanics of construction of the well, and the testing operations conducted as the well was drilled, are reviewed. The amount of observed recharge is mentioned, and tentative conclusions are drawn regarding the feasibility of the method. Utilization of such wells to store available excess hot waters from power plant operations is discussed.

Chase, D. E.

1947. Installation of a radial water collector: Am. Water Works Assoc. Jour., v. 39, p. 747–749.

A detailed description of the installation procedure of a radial water collector at West View, Pa., is presented.

Christiansen, J. E.

1945. (and Magistrad, O. C.). Report for 1944, laboratory phases of cooperative water-spreading study: U. S. Regional Salinity Lab., Riverside, Calif., 74 p.

Laboratory investigations of 43 undisturbed cores taken from soils in the San Joaquin Valley, Calif., are described. Permeability tests of the cores under conditions of prolonged submergence were made to determine the infiltration rates, locations of limiting permeability in the soil profile, effect of various treatments on soil permeability, and relation between field and laboratory percolation rates.

The infiltration curves were S-shaped. Dispersion and swelling of the soil particles caused the initial decrease in infiltration rate; removal of entrapped air by solution into the moving water caused the subsequent increase; and biological activity caused the final gradual decrease. During infiltration the permeability of the surface soil decreases more rapidly than that of the subsoil; consequently, after a period of infiltration the surface soil is usually much less permeable than the subsoil. The most practical and effective treatment for increasing recharge rates is periodic drying of the soil. Drying to any appreciable depth can be accomplished only by growing some crop on the soil which will rapidly remove the water stored within the root zone. The loosening of the soil by the plant roots may be an important factor. Without a crop, drying is confined to a shallow surface layer. Where the surface soil has an exceptionally coarse texture, the cores have higher rates than the field ponds; and where the soil is of fine texture, and especially if there is a clay subsoil, the cores have lower rates than the field ponds. Intensive study of undisturbed soil cores in the laboratory has proved to be successful in complementing field investigations. Certain processes can be studied in the laboratory which are not susceptible to field study.

Citizens General Water Advisory Committee

1934. Water conservation project—information regarding the 1934 well replenishment project: Santa Clara Valley Water Conserv. Dist., San Jose, Calif., 16 p.

This report describes a plan to conserve water in the Santa Clara Valley, Calif., by means of detention reservoirs in the mountains, by percolation in stream beds, and by diversion from streams for spreading and irrigation.

Clancy, G. E.

1947. Water from wells: Heating, Piping, and Air Conditioning, v. 19, no. 11, p. 75–79.

Disposal wells for returning cooling water underground are described. It is recommended that disposal wells be perforated only below the normal water table, and that supply wells be perforated only below the level of the bottom of disposal wells. These precautions will help prevent direct return flow from disposal to supply wells.

Clinton, F. M.

1948. "Invisible" irrigation on Egin Bench: Reclamation Era, v. 34, no. 10, p. 182–184.

This is a popular article describing artificial recharge of ground water through ditches for subirrigation of Egin Bench, Idaho. The water table is allowed to drop to 20 feet below ground surface and then is brought up to within about one foot during the growing season by recharging. The soil is porous volcanic sand.

Clyde, G. E.

1951. Utilization of natural underground water storage reservoirs: Soil and Water Conserv. Jour., v. 6, no. 1, p. 15–19.

In southern California artificial recharge of ground water is practiced over an area of 12,200 acres in which the average capacity is 0.83 foot per day. Furrow spreading wets less than 20 percent of the ground, but development and maintenance costs are low so the method is suitable where land is plentiful and cheap. Basin spreading wets over 75 percent of the area used, costs about $800 per acre to develop, including canals and control structures, and about $80 per acre annually for maintenance. Recharging through wells has been rather unsuccessful except where clear water is available under high heads.

Spreading costs vary widely, ranging from 85 cents to more than five dollars per acre-foot. This is cheap storage, however, because ground water in southern California may have a value of $35 to $40 per acre-foot. Typical spreading rates in southern California include 5 feet per day in San Antonio Creek, 2-3 feet per day in the San Gabriel area, and 3-10 feet per day in Tujunga Wash. Total artificial recharge in southern California in the last nine years amounts to 655,000 acre-feet.

As part of the Central Valley Project of California, it is planned to divert Class 2 water at Friant Dam, to convey it 165 miles by canal, and to recharge it underground near Bakersfield. The amount to be stored varies from 800,000 to 1,500,000 acre-feet annually. The spreading period is short and the value of land high; therefore, it is imperative that infiltration rates be kept high.

A cooperative research project established in 1944 near Bakersfield, Calif., is investigating causes of decreased infiltration rates with long submergence of spreading basins. Two sets of test ponds have been set up to study effects of chemical treatments, mechanical treatments, management practices, addition of organic matter, and vegetative trials. Four years of test pond work indicate that the best treatment is cotton gin trash which has been wetted for about 30 days and then allowed to dry. Recharge rates after the drying period started and remained high. In 1947 a laboratory was established at Bakersfield to study the soils and biological aspects of the problem.

Coe, J. J. *See* Banks, H. O., 1954.

Coffield, C. C.

1947. Horizontal type well increases ground water yield: Water Works Eng., v. 100, no. 7, p. 346–349.

The installation of a Ranney collector well at Parkersburg, W. Va., bordering the Ohio River is described and illustrated.

Conkling, H. *See also* Baker, D. M., 1930.

1936. Symposium on contribution to ground-water supplies—General discussion: Am. Geophys. Union Trans., v. 17, pt. 2, p. 479–480.

Natural percolation from rainfall on uneven ground exceeds that from water spread on artifically leveled areas because of greater concentrations of water in depressions. Percolation contributions to ground water can be determined by preparing a water budget of the basin. An investigation of the economics of water spreading is recommended to evaluate properly benefits from conservation to ground water and from decreased pumping lifts. Spreading areas are most effective in flat porous valleys, whereas steeply sloping

valleys require surface reservoirs to contain floodwaters for more effective spreading.

In portions of the San Joaquin Valley, Calif., spreading takes the form of extra irrigation whenever water is available for the direct purpose of inducing percolation.

1946a. An imported water supply for West Basin, Los Angeles County, California: West Basin Water Assoc., Los Angeles, 35 p.

An appendix to this report discusses the feasibility of sewage reclamation as a source of additional water for West Basin District, Los Angeles County, Calif. Sewage would be treated, distributed through mains over the area, and injected through wells underground. For this project an average of 1 cfs recharge was assumed for a 16-inch well 400 feet deep. During much of the time wells can be recharged at 2 cfs, allowing for rotation of recharging and equalization of ground water near the wells. Each recharge well would be equipped with modulating-type check valves to prevent water hammer and to control flow. Wells would be housed under derrick houses and surrounded with a fence and gate.

1946b. Utilization of ground-water storage in stream-system development: Am. Soc. Civil Engineers Trans., v. 111, p. 275–354.

Measurements of stream-bed percolation in the San Gabriel River, Calif., showed rates varying from 1.78 to 9.6 feet per day. Relationships established between percolation and discharge for the San Gabriel River have been applied to similar coastal streams of California.

Six recharge wells have been constructed and operated in Orange County. Calif. The wells are located on the periphery of a 70-acre spreading ground. Storm-water is permitted to flow over the entire spreading area. The water is absorbed and cleared of silt by the sandy soil, and then drains into a system of 6-inch tile drains laid in rock-filled trenches at an average depth of 10 feet below the surface. These drains empty into each side of 4-foot-square redwood intake cribs constructed around each well. The recharge wells consist of 12-inch perforated steel casings extending to depths of nearly 400 feet. The cribs bottom at less than 100-foot depths.

Artificial recharge has been practiced for more than 30 years at the Perth Amboy Water Works, Perth Amboy, N. J., where spreading rates ranging from 0.01 to 0.28 foot per day have been measured. Water spreading is practiced at several places in New Jersey. In Long Island, N.Y., recharging of glacial beds by means of wells and pits is conducted.

To replenish the ground-water supplies of the Ruhr Valley, Germany, river water is conducted to off-stream spreading grounds, which are basins excavated through a layer of clay into gravel. These basins are floored with sand which is cleaned occasionally. Near the city of Haltern, Germany, a sheet-pile cutoff was built on the Stever River to form two reservoirs. From these reservoirs water is diverted to spreading grounds to augment the ground-water storage.

Cooper, H. H., Jr. *See* Unklesbay, A. G., 1946.

Council of the City of Columbus.

1935. Ordinance No. 225–35: Columbus, Ohio.

An ordinance of Columbus, Ohio, provides that well water used for cooling purposes shall be returned to the earth by an additional drilled well or wells for such purpose.

Crandall, Lynn. *See also* Stearns, H. T., 1938; 1939.

1953. Ground-water flows of the Snake River plain: U. S. Geol. Survey open-file report (paper delivered at annual convention of Idaho State Reclamation Assoc., Pocatello).

To meet water needs for irrigation in the Snake River plain, Idaho, various proposals are discussed to make available surplus floodwaters. As much of the area is underlain by porous lava formations, canals are suggested to distribute and recharge the water underground. Studies in one area revealed infiltration rates of 0.8 foot per day during a 3-month spring period. Recharge canals might also be built with only a lower bank, allowing the water to back up into draws and depressions. Recharge under such circumstances is estimated at 1.0 foot per day. Another possibility is direct recharge to lava formations by disposal wells. A small group of 8-inch disposal wells about 100 feet deep have recently been constructed near Roberts. These are reported to be absorbing about 2 cfs per well. Larger wells should handle considerably greater flows. Disposal wells tend to become partially clogged with continued use; but proper methods of construction and maintenance could probably overcome this difficulty.

Crider, A. F.

1906. Drainage of wet lands in Arkansas by wells: U. S. Geol. Survey Water-Supply Paper 160, p. 54–58.

This water-supply paper reviews the work on disposal wells in Michigan by Horton and in Georgia by McCallie and reports the failure of disposal wells to drain the flat lands of northeastern Arkansas. Failure is attributed to the high content of clay in the surface soils, which is carried into and seals the wells.

Crosthwaite, E. G. *See also* Ferris, J. G., 1954.

1954. Ground-water development and problems in Idaho: U. S. Geol. Survey open-file report (paper presented at annual convention of Idaho State Reclamation Assoc., Twin Falls), 17 p.

The opportunities, methods, information required, and advantages of artificial recharge, using surplus Snake River water in Idaho to augment ground-water supplies, are described.

Cushing, E. M. *See* Babcock, H. M., 1942.

DeBuchananne, G. D. *See* Barksdale, H. C., 1946.

Davids, Herbert W.

1951. (and Lieber, Maxim). Underground water contamination by chromium wastes: Water and Sewage Works, v. 98, no. 12, p. 528–529.

In Nassau County, N. Y., during World War II, industrial wastes containing chromium were recharged to the ground-water body. The contaminant was detected first in 1942 and was studied in more detail in 1947. Waste-treatment plants completed after 1948 by the large consumers of chromic acid were successful in removing chromium almost completely from waste waters. The quality of the ground water in the contaminated areas should improve in time because of dilution. Further toxicological studies are necessary to determine a safe limit for hexavalent and total chromium in drinking waters. *RRB*

Dechant

1936. Grundwasseranreicherung für das Stadtwaldwasserwerk in Bamberg (Ground-water recharge for the city forest waterworks at Bamberg): Gas- u. Wasserfach, v. 79, no. 3, p. 36–39.

The waterworks for Bamberg, Germany, uses water from several small nearby streams. The water is first collected in settling basins where a large portion of suspended matter is removed. Next it is recharged underground through infiltration basins. Recharge rates up to 7.2 feet per day are continually obtained. The water is then pumped from 55 nearby wells for distribution to the city.

Denner, J.

1933. Die künstliche Anreicherung des Grundwassers (The artificial recharge of ground waters): Deutsche geol. Gesell. Zeitschr. v. 85, no. 7, p. 511–522.

A generalized scheme of artificial recharge of ground waters in river basins, including source, storage, and recharge areas is outlined. The upstream source area furnishes water to the river and also to the aquifer. The storage area, which is downstream from the source area, stores water back of dams for distribution to the recharge area. The recharge area, located in the lower portions of the basin, contains the artificial-recharge developments for ground-water storage and the installations for collecting the ground water for use. Examples of artificial-recharge operations at Essen, Sassnitz, Munster, Berlin, Stuttgart, Breslau, and Cologne, all in Germany, are presented to illustrate how the scheme can be applied in actual practice.

1934. Die wasserwirtschaftliche Bedeutung der künstlichen Anreicherung des Grundwassers unter besonderer Berücksichtigung der Wasserwirtschaft Gross-Berlin (The importance of artificial recharge of ground water with special reference to the water economy of greater Berlin): Gas- u. Wasserfach, v. 77, no. 24, p. 413–415; no. 25, p. 429–433; no. 26, p. 444–447; no. 27, p. 462–467.

Present and future applications of artificial recharge of ground water for water supplies in Germany are described, together with schemes for water storage and conservation in river basins. The place of artificial recharge in mining is discussed and illustrated with examples. Describes, in connection with the water supply for Berlin, Germany, the use of impounding reservoirs on the Spree and Havel Rivers for water conservation by artificial recharge, and for flood control. An extensive bibliography of German literature is appended.

DeRance, C. E.

1884. On a possible increase of underground water supply: Soc. Arts Jour., v. 32, London, p. 851–854.

The use of "dumb-wells" is advocated for recharging storm surface water underground to raise the water table in the porous chalk formations of England and Wales. It is recommended that care be taken in constructing these wells so that objectionable material will not be carried into the wells and contaminate the ground water.

Dewey, H.

1933. The falling water level of the chalk under London: Water and Water Eng., v. 35, no. 421, p. 440–447.

This article discusses the falling water table in the chalk aquifers underlying London and means of controlling it. Recharge wells and soakaways have been suggested using various fresh-water supplies. Lack of adequate filtration increases dangers of contamination and pollution of underground water supplies. Recharge wells can be used successfully where sufficient surface water is available, when the water is clear and free of all impurities, and where the recharge well is so located that water will flow toward the depleted area.

Eaton, C.

1943. Report on percolation rates in sinking basin no. 3 of Kaweah Delta Water Conservation District: U. S. Bur. Reclamation, Sacramento, Calif., 6 p.

Installation and operations of a spreading basin in Tulare County, Calif., is described. The basin covers an area of 134 acres, and is formed by levees six feet high on all sides. The bottom of the basin is rough, having differences in elevation of six feet, and intersects an old slough channel. In 1942 the average recharge rate was 0.34 feet per day for 50 days. Lateral ground-water flow after the last inflow to the basin continued for 200 days and covered an area of 8,000-foot radius. In 1943 water was spread for 159 days at a maximum recharge rate of 1.0 foot per day, the average rate during the first 44 days being 0.54 foot per day and for the entire period 0.42 foot per day.

Eaton, E. C.

1930. Preliminary outline of ultimate plan (Los Angeles County Flood Control District) : California Div. Water Resources Bull. 32, p. 13–23.

The flood-control plan for Los Angeles County, Calif., includes regulation of mountain floodwaters at a rate of flow where they may be caused to percolate through spreading basins; it also, includes development to the fullest extent of the natural spreading areas into spreading basins, permitting maximum absorption of floodwaters. Studies and measurements have shown that on a conservative and practical basis it is possible to absorb 8.9 feet per day of water over the wetted area. This may be done by spreading basins or ditches. Maximum recharge is obtained by spreading in a thin sheet over a large area. It is advisable to maintain over a spreading area a flowing stream with a velocity sufficient to scour silt deposits from the surface so as to avoid sealing of the surface.

In areas where spreading ditches are not feasible, open bottom channels of as great width as practicable should be maintained and surface areas should be scarified to a depth of six inches or more at frequent intervals before flow periods.

1931. Comprehensive plan for flood control and conservation: Los Angeles, Los Angeles County Flood Control District, 60 p.

This report describes plans for flood-control works in Los Angeles County, Calif., including provisions for spreading grounds for recharging floodwaters. Percolation rates depend more upon the area covered than upon the depth of water. Spreading tests below Big Dalton Dam using water heavily charged with muck and silt showed that sealing up occurred with ponding, but that there was no diminution in percolation rates when moving water was used.

In areas where top strata of impervious materials occur, spreading is not feasible. Replenishment tests by shafts and wells have been shown to be feasible provided the water is suitably desilted.

Engler, K.

1945. (and Thompson, D. G., and Kazmann, R. G.). Ground water supplies for rice irrigation in the Grand Prairie Region, Arkansas: Arkansas Univ. Bull. 457, Agr. Exp. Sta., Fayetteville, 56 p.

To prevent future overdraft in the Grand Prairie region of Arkansas, artificial recharge is suggested. Because of the overlying impervious clay bed and the considerable depth to the water-bearing strata, recharge by wells is recommended. The problems of water quality, sediment, algae, and bacterial growths are mentioned in connection with recharge wells. Recharge wells should be drilled and tested to determine whether recharge is practicable.

Erickson, E. T.

1949. Using runoff for ground-water recharge: Am. Water Works Assoc. Jour., v. 41, p. 647–649.

An experimental recharge of wells near Newark, N. J. is described. Excess runoff was transported 25 miles through an available high-pressure fire system and injected into 5 wells. An average recharge of 0.60 cfs per well was maintained for more than two months. Water levels showed a net rise of about 30 feet.

Etcheverry, B. A.

1936. (and Haehl, H. L.). Report on conservation of controlled flood waters of San Gabriel River: Los Angeles, Los Angeles County Flood Control District, 109 p.

This report presents a comprehensive analysis of the hydrology of the San Gabriel Basin, Los Angeles County, Calif. As part of the flood-control program, spreading grounds are recommended for conservation of floodwaters.

1939. Supplemental report on water supply from Central Valley Project required for lands in Kern County: Report to Kern County Water Assoc., Bakersfield, Calif., 24 p.

Experiments in water spreading, using ponds and sloped checks, were conducted in 1938 and 1939. Recharge rates for six ponds for periods of 61 to 92 days averaged 0.99 foot per day in 1938 and 0.67 foot per day in 1939.

Silt accumulation during the 1938 and 1939 season, algae growth in the late 1938 ponding period, and the effect of plowing prior to the 1939 season, reduced the average rate of recharge for the 1939 season considerably below that of the 1938 season. Algae growth late in the 1938 season, for which there was no prolonged treatment by copper sulfate, reduced the rate of percolation during the last ten days of ponding to about 0.22 foot per day.

The following conclusions were drawn from the study. Silt accumulation and plowing reduce the rates of percolation less for coarse soils than for less previous soils; the prevention of algae growth by treatment with copper sulfate and intermittent removal of silt by scraping should be considered; the use of settling basins through which the water would pass before discharging into ponds should also be considered. Growing of some kind of crop in the ponds to develop root systems which would assist in maintaining percolation channels through the topsoil should be investigated. The sloped-check method of

water spreading demonstrated the feasibility of using flowing water to prevent silt deposition and algae growth.

Fair, G. M. *See* Scheelhaase, F., 1924.

Federick, J. C.

1948. Solving disposal problems in unsewered areas: Sewage Works Eng., v. 19, no. 6, p. 292–293, 320.

Field measurement of percolation rates in pits is described and results are applied to design of septic tank disposal systems. Disposal rates approach 0.1 foot per day after initial application.

Ferris, J. G.

1949. Ground water, *in* Hydrology, by C. O. Wisler and E. F. Brater: New York, John Wiley and Sons, chap. 7, p. 198–272.

Methods of artificial recharge are summarized (p. 265–268), and recharge projects in San Gabriel Valley, Calif., Long Island, N. Y., and Louisville, Ky. are mentioned. *RCV*

1950. Water spreading and recharge wells: Indiana Dept. Conserv., Div. Water Resources, Water Conserv. Conf. Proc., p 52–59.

Methods of artificial recharge are summarized and important projects in the United States are described. Based on available data, the following table gives reported recharge rates for different areas and methods:

Location	Recharge method	Recharge rate	Location	Recharge method	Recharge rate
		Feet per day			*Feet per day*
California-Tujunga Wash	Basin	6	California-Lytle Creek	Ditch	0. 8–11
California-Saticoy	do	3	New Jersey-Perth Amboy	do	0. 009–0. 38
California-Azusa	do	1. 2–9			*Cfs*
California-Anaheim	do	0. 8–3	California-Lytle Creek	Well	0. 6–1. 9
New Jersey-Perth Amboy	do	2. 3	New York-Long Island	do	0. 5–2. 2
New Jersey-East Orange	do	0. 4–0. 5	Florida-Orlando	do	22
New York-Nassau County	Pit	0. 8–31	California-Lytle Creek	Shaft	2. 0
California-Lower Santa Ana R.	Ditch	3			

1954. (and Burt E. M., Stramel, G. J., and Crosthwaite, E. G.). Ground-water resources of southeastern Oakland County, Michigan: Michigan Geol. Survey Div. Prog. Rept. 16, 158 p.

This paper reviews (p. 54–58) induced infiltration from both underground and surface sources and (p. 144–149) management of water resources including artificial recharge. *RCV*

Flinn, A. D.

1927. (and Weston, R. S., and Bogart, C. L.). Water works handbook of design, construction, and operation, 3d ed.: New York, McGraw-Hill Book Co., Inc., 871 p.

The chapter on infiltration galleries (p. 260–265) describes and illustrates various gallery installations in the United States and Germany. Galleries either collect seepage water from a stream or intercept recharged water applied to filter basins. Galleries intercept water more completely than wells and cost less for preliminary investigations. The cost of pumping from galleries is

lower than the cost of pumping from wells, and there is lower depreciation but higher construction costs. Galleries should be installed only where water tables are stable and sufficient quantities of water are available. Sealing of porous strata surrounding a gallery will curtail yield unless means for cleaning are provided. Infiltration rates of 0.03 to 0.08 foot per day over the area drained by galleries may be expected from a properly designed system.

Foose, R. M.

1951. Ground water conservation and development: Pennsylvania Dept. Int. Affairs. Monthly Bull., v. 19, no. 2, p. 17–28.

In the Hershey Valley, Pa., a serious lowering of the ground-water table occurred in 1949 as a result of heavy pumping during deep limestone quarrying operations. Besides dewatering the limestone aquifers, the heavy pumping caused many sinkholes to develop in the overdraft area. To raise water levels a program of well recharging was inaugurated. This, together with grouting to seal off openings carrying water into the quarry, succeeded in returning the water table to nearly normal levels.

1953. Ground-water behavior in the Hershey Valley, Pennsylvania: Geol. Soc. America Bull., v. 64, no. 6, p. 623–645.

A section of the paper (p. 642–644) describes artificial recharge of limestones in Hershey Valley. Temperature and water-level measurements were used to study effects of recharging good-quality water through wells at rates of 2.7 to 7.8 cfs. *RCV*

Forbes, H.

1921. Underground water storage on the Santa Ana cone: Eng. News-Rec., v. 87, no. 17, p. 683–684.

Winter flows of the Santa Ana River, San Bernardino County, Calif., are diverted over its alluvial cone to recharge ground water. The operation was begun in 1911 and consists of spreading water into numerous streams and impounding ponds. Studies of the effectiveness of this program indicate that 20,000 acre-feet in 1914 and 13,000 acre-feet in 1915 were conserved that would otherwise have been wasted. As a result of the spreading the water table has been built up so that larger ground-water supplies are available for ensuing dry years.

Freeman, V. M.

1936. Water-spreading as practiced by the Santa Clara Water-Conservation District, Ventura County, California: Am. Geophys. Union Trans., v. 17, pt. II, p. 465–471.

The Santa Clara Water-Conservation District, situated in the Santa Clara River Valley and Oxnard Plain, Ventura County, Calif., established three water-spreading grounds. These are located near the cities of Saticoy, Santa Paula, and Piru. The Saticoy spreading ground receives water from the Santa Clara River which is diverted by temporary earth dams. The spreading system consists of 33 basins varying in size from 1.2 to 6.0 acres and totaling 97 acres. Topsoil is Yolo fine sandy loam and depth to the water table ranges from 75 to 90 feet. Recharge rates in 1935 averaged about 1.8 feet per day.

Santa Paula spreading ground receives water diverted from Santa Paula Creek by a small rock-and-gravel dam. Ninety-seven small spreading basins have been formed in overflow channels of the creek by construction of loose

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rock check dams. Topsoil is of a river-wash type and depth to ground water is about 100 feet at start of season. No data on recharge are presented in the report.

The Piru spreading ground obtains water diverted from Piru Creek by temporary rock-and-gravel dams. Nine basins total 43.2 acres. Topsoil is Yolo gravelly fine sandy loam; depth to the water table ranges from 130 to 160 feet. Recharge rates averaged about 1.2 feet per day over the entire 5-month season. No water containing more than 20 cubic feet of suspended matter per acre-foot is spread. Loads of suspended matter are reduced to this limit within 2 to 10 days after peak flows.

In the Saticoy spreading ground the area has not been cultivated, the natural vegetation has not been disturbed, and there is no noticeable reduction in the percolation rate at the beginning of the season after 6 years. The Piru spreading ground was cleaned after 2 years of operation by removing 2 to 4 inches of silt to increase stream-bed percolation. About 2½ miles of stream bed of the Santa Clara River were scarified by a heavy road scarifier after storms each year. Increased percolation during two seasons averaged about 14.3 acre-feet per day per mile of stream channel. It is suggested that the depth to ground water is one of the fundamental factors affecting the capacity of a spreading ground. The estimated annual capacity of the Saticoy works is 200 feet of water when the water table is initially 80 feet deep. Spreading-operation costs averaged 18.3 cents per acre-foot in the 1934–35 season.

Fuller, M. L. *See also* Hall, C. W., 1911.

1911. Drainage by wells: U. S. Geol. Survey Water-Supply Paper 258, p. 6–22.

A general discussion of disposal wells covers the following topics: suitable geologic conditions, effectiveness in different materials, construction, capacity, cost, causes of failure, uses, and pollution resulting from use of disposal wells.

Gale, S. H. *See* Piper, A. M., 1939.

Gandenberger, W.

1950. Grundlagen der Grundwasseranreicherung (Fundamentals of ground-water recharge) : Gas- u. Wasserfach, v. 91, no. 12, p. 142–149.

This paper presents an excellent description of the basic principles of artificial recharge of ground water. The various combinations of wells and infiltration basins adjacent to rivers are sketched to show direct recharge and induced infiltration methods. A review of the historical development of artificial recharge in Europe is followed by a discussion with examples of the various recharge methods: water spreading, infiltration ditches, infiltration basins, recharge wells, and infiltration galleries. Water treatment required for recharging is discussed in terms of the method used, recharge rates, and maintenance. Artificial recharge of ground water is compared with direct treatment of surface water for water supply. Considered in the comparison are space requirements, water requirements, aesthetic considerations, operating difficulties, overload and enlargement capabilities, water quality, and chemical treatment. Preliminary geologic and hydrologic investigations required for artificial-recharge installations are described.

Garber, W. F. *See* Stone, Ralph, 1952.

George, W. O.

1952. Recharge of Texas' underground water reservoirs: Tex. Board Water Engineers dupl. rept., 7 p.

Several artificial recharge operations are briefly discussed.

Gidley, H. K.

1952. Installation and performance of radial collector wells in Ohio River gravels: Am. Water Works Assoc. Jour., v. 44, p. 1117–1126.

A description of radial collector wells along the Ohio River in West Virginia, notes on the geology of the area, and general information on the construction of radial wells are presented. Well yields, costs, and quality of water obtained are discussed. *GWS*

Gieseler, E. A.

1905. A new form of filter gallery at Nancy, France: Engin. Rec., v. 51, no. 6, p. 148–149.

The water supply for Nancy, France, in the 1890's was obtained from filter galleries in alluvium bordering the River Moselle. In order to increase the yield of the system in 1899, Dr. E. Imbeaux installed a surface filter gallery. This consisted of a supply pipe bringing river water onto the land where it was discharged into 6.6-foot deep sand-filled trenches. These trenches filtered the water and permitted it to collect in the galleries.

The yield of the system doubled with the new trenches. The sand must be replaced about every five years, but this can be done in sections so that the entire system need not be shut down. Filtration through the sand and into the galleries removes about 93 percent of the river-water bacteria.

Glover, R. E.

1954. (and Balmer, G. G.). River depletion resulting from pumping a well near a river: Am. Geophys. Union Trans., v. 35, no. 3, p. 468–470.

A well adjacent to a river will take a portion of its supply from the river. A theoretical formula is developed which permits the draft on the river to be computed in terms of the distance of the well from the river, the properties of the aquifer, and time. The formula applies where the river can be considered to flow in a straight course which extends for a considerable distance both upstream and downstream from the well location.

Gorman, A. E.

1946. Water-supply practice in Germany—1945: New England Water Works Assoc. Jour., v. 60, no. 2, p. 132–152.

One common method of collecting water for public systems in Germany is use of infiltration galleries adjacent to rivers or artificial recharge areas. Gallery installations at Essen, Hagen, Munich and Nuremberg are briefly described. The water supplies from these galleries are of high quality, requiring only chlorination, and have uniform, cool temperatures.

Gotaas, H. B. *See* Greenberg, A. E., 1952; Stone, R. V., 1952.

Goudey, R. F.

1930. Sewage reclamation plant for Los Angeles: Western Construction News, v. 5, no. 20, p. 519–525.

As part of a new sewage reclamation plant at Los Angeles, Calif., treated sewage is recharged into five spreading beds. Beds were formed by removing the top 15 inches of soil and exposing deep sand and gravel deposits. The water table stands 15 to 35 feet below ground surface. The theoretical recharge rate of the beds is 0.6 foot per day, although one bed has an overall

effective rate of 3.0 feet per day. Fourteen 2-inch wells have been sunk around the beds to study physical and chemical changes of the ground water.

1931a. Plans for sewage reclamation in the Los Angeles metropolitan area: Eng. News-Rec., v. 106, no. 11, p. 443–446.

One use of reclaimed sewage is to replenish ground-water supplies. Water from an experimental sewage-treatment plant is recharged into natural sand beds, and a close check is kept on the various chemical changes occurring underground.

Reclaimed water may be wastefully recharged underground during a series of dry years, if in a following series of wet years the ground-water basins are surcharged, causing waste of large flood flows.

1931b. Reclamation of treated sewage: Am. Water Works Assoc. Jour., v. 31, no. 2, p. 230–240.

Effluent from a sewage treatment plant in Los Angeles, Calif., is recharged through five spreading grounds. These are used both continuously and intermittently. One bed in which chlorine is used has been in continuous operation for over three months. Recharge rates up to 3 feet per day appear feasible. The water table is 25 feet below ground surface.

1931c. Reclamation of treated sewage: Water Works and Sewerage, v. 78, no. 1, p. 3–7.

Same material as Goudey (1930) on Los Angeles sewage treatment plant is presented.

Greenberg, A. E.

1952. (and Gotaas, H. B.). Reclamation of sewage water: Am. Jour. Public Health, v. 42, no. 4, p. 401–410.

This paper describes a field investigation of spreading treated sewage near Lodi, Calif. Results indicated that: bacteriologically safe water can be produced from a good sewage plant effluent; a water of satisfactory chemical quality can be produced from the final effluent of a plant treating domestic sewage; a percolation rate of about 0.1 foot per day or more can be expected when a final sewage plant effluent is spread on Hanford fine sandy loam; resting and spading of the spreading basin will keep percolation rates at a maximum; and that mosquitoes and algae need to be controlled on spreading ponds.

Gross, E.

1929. Die Gewinnung von Grundwasser und seine künstliche Erzeugung (The collection of ground water and its artificial generation): Gas- u. Wasserfach, v. 72, no. 37, p. 901–905.

The basic principles of artificial recharge of ground water by using settling and infiltration basins bordering a river are described. To obtain adequate supply, recharge basins should be designed on the basis of a recharge rate of 1.6 feet per day. A layer of about 18 inches of filter sand placed upon the bottom of infiltration basins is recommended. The retention time of recharged water in the ground before pumping should be at least in the range of 40 to 100 days; thus the greater the permeability the greater the distance necessary between recharging and pumping locations.

The installation at Wiesbaden, Germany, along the Rhine River is shown as an example of the method.

Grunsky, C. E.

1898. Irrigation near Fresno, California: U. S. Geol. Survey Water-Supply Paper 18, 94 p.

This paper contains data on measurements of seepage water loss from irrigation canals in Fresno County, Calif. Large variations were noted because of soil type, canal size, and condition of the canal. All canals were unlined. Measurements of water loss in the Kings River and Fresno Canal ranged from 1.25 to 3.77 cfs per mile; in the Fresno Canal, 0.74 to 8.49; and in the Centerville and Kingsburg Canal, 15.63 to 52.35.

Guerrée.

1954. La réalimentation artificielle des nappes d'eau souterraines (Artificial recharge of aquifers) : Technique de l'Eau, v. 8, no. 91, p. 19–24, 32.

History of recharge experiments is reviewed, citing the use of a filtration gallery at Glasgow in 1810 as the first in ground-water-recharge operations. The second was at Toulouse in 1820. *RCV*

Guyton, W. F. *See also* Klaer, F. H., 1948a.

1944. (and Stuart, W. T., and Maxey, G. B.). Progress report on the ground-water resources of the Louisville area, Kentucky: Kentucky Dept. Mines Minerals Geol., Div., 20 p.

This report suggests the development of additional supplies of underground water by induced infiltration from the river, recharge through wells and basins, and construction of wells in outwash deposits southwest of Louisville, Ky.

1945. Depleted wells at Louisville recharged with city water: Water Works Eng., v. 98, no. 1, p. 18–20.

A general description is given of the recharge of city water through industrial wells during the spring of 1944 to build up underground water storage for summer demands at Louisville, Ky.

1946. Artificial recharge of glacial sand and gravel with filtered river water at Louisville, Kentucky: Econ. Geology, v. 41, no. 6, p. 644–658.

To alleviate a serious overdraft in Louisville, Ky., distilleries in the spring of 1944 recharged water underground through wells. For a period of about three months cold water from the municipal river-water supply was recharged at rates as high as 2.6 cfs. While this water was being added to the aquifer through several supply wells, the distilleries used only city water. In this way the large cone of depression in the water table created by heavy pumping was practically filled. During the following summer when the city water became too warm to be used as cooling water in the plants, an increased and ample supply of cold water was available from the wells.

Haehl, H. L. *See* Etcheverry, B. A., 1936.

Halberg, H. N.

1949. (and Roberts, C. M.). Recovery of ground-water supplies by pumping from water-table ponds: Am. Geophys. Union Trans., v. 30, no. 2, p. 283–292.

This report summarizes a study made of ground-water conditions in the vicinity of Fresh Pond, a water-table pond from which water is pumped as part

of the public supply of the City of Cambridge, Mass. The fluctuations in water levels in observation wells near the pond indicate ground-water contributions to the pond when it is at low stage and increases in ground-water storage when the pond is at high stage. Thus, recharging the glacial deposits in the vicinity of the pond can be considered as a means of storing, for later use, a supply of water over and above that which can be stored in the pond itself.

Hall, C. W.

1911. (and Meinzer, O. E., and Fuller, M. L.). Geology and underground waters of southern Minnesota: U. S. Geol. Survey Water-Supply Paper 256, 406 p.

The use of wells for disposal of water on wet lands in southern Minnesota is mentioned. Near Albert Lea, Minn., a 3-inch well disposed of water from an area of 5 acres.

Hall, W. M.

1917. The water supply of Parkersburg, West Virginia: Am. Soc. Civil Engineers Trans., v. 81, p. 749–849.

This paper describes the process of selecting a new water supply for the City of Parkersburg, W. Va.; the investigation of the possible sources of supply, especially the natural underground supply in the neighboring Ohio River bottoms and plateau; the physical and geological phenomena relating thereto; the methods considered for collecting the water for pumping; and the novel method finally adopted. The method consists of an infiltration system composed of strainer pipes laid in the bed of the river and overlain by a bed of washed gravel and sand.

Harrell, M. A.

1935. Artificial ground-water recharge—a review of investigations and experience: U. S. Geol. Survey open-file report, 34 p.

Records of water-spreading operations in the United States date back to 1889, considerable work having been done in California in the last 30 years. Recharge through wells was attempted in Los Angeles in 1927. Water was permitted to flow into a group of wells 20 inches in diameter and 400 feet deep which normally flowed at 5-6 cfs per well. Initially the wells took considerable water, but after a week or so recharge was stopped because the recharge rate had diminished to the point where continued efforts were not justified. Walls had to be reconditioned before placing them back in normal operation because silt and debris had clogged them.

A well in southeastern Los Angeles took water at a rate of 0.26 cfs for a period of 92 days in 1933. This well, 16 inches in diameter and 300 feet deep, was dug in gravel deposits. The water table was 93 feet below ground surface and the recharge head was 65 feet above the water table.

Recharge of water through a well into a confined aquifer at Manhattan Beach, Calif., in 1934 indicated that the rate of percolation increased with larger recharge heads. The recharge rate for this well was only one-quarter that of another well screened in an unconfined aquifer consisting of coarser materials.

Florida disposal wells, Long Island recharge wells, water flooding of oil sands, and brine disposal are also discussed. Recharge water must be clear to avoid clogging the wells and must be relatively free of bacteria.

Haupt, H.

1933. Trinkwassergewinnung durch Infiltration und Aufbereitung von Oberflächenwasser (Drinking water supply by infiltration and purification of surface water): Gas- u. Wasserfach, v. 76, no. 16, p. 279–283.

This article presents a general discussion of artifical recharge and sand filtration for improving surface-water supplies for domestic use. Particular emphasis is placed on water quality.

Hedger, H. E. *See also* Arnold, C. E., 1949.

1950. Los Angeles considers reclaiming sewage water to recharge underground basins: Civil Eng., v. 20, no. 5, p. 323–324.

To develop additional water supplies for Los Angeles County, Calif., consideration is being given to reclaiming sewage and to recharging it underground. Several locations can be utilized for this purpose, and cost estimates on a 50-year basis range from $9.30 to $18.00 per acre-foot of treated effluent, depending upon location and existing available facilities. Experimental spreading tests in 1949 near Whittier and Azusa sewage treatment plants showed that percolated effluents were bacteriologically safe within 7 feet of ground surface, that alternate weekly periods of percolation and of resting and cultivation would be necessary, and that an over-all average spreading rate of 0.51 foot per day could be used for design purposes.

Heiple, L. R. *See* Steinbruegge, G. W., 1954.

Hendrixson, W. W. *See* Norton, W. W.. 1912.

Henkel, K.

1952. Böschungsfestigung der Becken für die künstliche Grundwasseranreicherung (Slope protection of basins for artificial ground-water recharge): Gas- u. Wasserfach, v. 93, no. 10, p. 297–298.

Artificial recharge basins in the Ruhr area of Germany are designed for an infiltration rate of about 4 feet per day. Basins measure 500 to 1,300 feet in length, 65 to 160 feet in width, and 8 to 10 feet in depth. Originally side slopes were not protected, but stability under prolonged submergence and drying and ready access for cleaning and maintenance were improved by slope protection. A recommended slope surface consists of an interlocking concrete block wall on a slope of 1:1.25. Block dimensions are 24 by 20 by 3 inches.

Hess, R. W.

1953. 1952 industrial wastes forum: Sewage and Ind. Wastes, v. 25, no. 6, p. 706–728.

A transcript of a panel discussion on subsurface disposal of waste liquid is included (p. 715–720).

Hicks, J. N.

1942. A report pertaining to water spreading on the Upper Santa Ana River delta: Berkeley, California Univ., BS Thesis, 49 p.

An analysis of water spreading, and discussion of results, benefits, and most economical methods for the upper Santa Ana River delta, Calif., is presented.

Hill, R. A.

1936. (and Whitman, N. D., Jr.). Percolation from surface-streams: Am. Geophys. Union Trans., v. 17, pt. II, p. 477–478.

Qualitative results of sand-model experiments on stream-bed percolation are described. Using bluing as a dye the flow patterns in a transverse cross-section through a model valley were observed through a glass panel. A ground-water ridge was built up to the stream bed by vertical percolation. When the ridge reached the stream bed, flow took place laterally and vertically. Flow nets were constructed for various symmetrical and unsymmetrical conditions.

Hofmann, O. D.

1936. (and Jordan, L. W.). Report on the investigation of the San Antonio grounds: Los Angeles, Los Angeles County Flood Control Dist., 53 p.

This report covers preliminary investigations of spreading grounds along San Antonio Creek, Los Angeles County, Calif. Percolation rates were 2.6 feet per day for main supply ditches; 6.2 feet per day for distributory ditches, gullies at their ends, and laterals; 1.5 feet per day for ends of laterals; and 0.97 foot per day in the main wash. Recharge capacities have been reduced by erosion which has narrowed the ditches and reduced the wetted area, and by sealing from silty flows. Spreading costs per acre foot were about $0.16 during years of normal flows with increased costs for years of subnormal flow.

Holthusen, W.,

1928. Das Grundwasserwerk Curslack, ein weiterer Schritt zur Loslösung der Hamburger Wasserversorgung von der Elbe (The Curslack ground-water works, a further step toward separating the Hamburg water supply from the Elbe) : Gas- u. Wasserfach, v. 71, no. 38, p. 913–924.

In describing the history and development of the Hamburg, Germany, water supply, the artificial recharge installation at Curslack is discussed. The plant consists of two long parallel trenches which recharge surface water underground. Between the two trenches is a line of wells which pump the recharged water for use. The trenches are each about four miles long and 20 feet wide, and have sloping concrete sides. Sand occupies the trench bottoms. The trenches are located about 325 feet on each side of the line of wells.

1933a. Fünf Jahre Grundwasseranreicherung in Curslack (Five years of supplementing ground water at Curslack) : Gas- u. Wasserfach, v. 76, no. 27, p. 525–528, no. 28, p. 545–552.

Over 90 percent of the water supply for Hamburg, Germany, is from ground water recharged artificially. River water is applied to seepage ponds and then pumped from wells for use. Measurement of salt travel showed that two months were required for water to travel 280 feet from a seepage pond to a well. The pumped water is superior to treated surface water, the bacterial count never exceeding 2 per cc, and B. coli has never been found in 100 cc samples.

1933b. Fünf Jahre Grundwasseranreicherung in Curslack. (Five years of supplementing ground water at Curslack) : Deutscher Ingenieure Ver. Zeitschr., v. 77, no. 37, p. 1013.

Water furnished by the new Curslack ground-water supply of Hamburg, Germany, is obtained by percolating surface water over a 5500-acre area in which are located 272 wells. Each well has a 55-yard protective strip around it and pumps water from a sand stratum about 40 feet thick whose upper surface is about 18 feet below ground level. As much as 45 cfs, or 60 percent of the supply, is taken for recharging from the Elbe and Bille Rivers and a drainage ditch. Only minor changes have occurred in water quality during five years of operation. Temperature has risen from 9.2° C to 9.5-9.8° C. Bacterial count is usually zero, and always less than two organisms per cc. B. coli could not be detected in 1000 cc. portions. Iron, manganese, and carbon dioxide have recently increased but the rise has now ceased. Because of increased carbon dioxide content, a deacidification plant is being built.

Hood, J. W. *See* Sundstrom, R. V., 1952.

Horberg, L.

1950. (and Suter, M., and Larson, T. E.). Groundwater in the Peoria region: Illinois State Water Survey Bull. 39, 128 p.

To study the feasibility of restoring ground water by land flooding at Peoria, Ill., experiments were conducted in an abandoned gravel pit. Water was pumped from the Illinois River at an approximate rate of 4.9 cfs, chlorinated, and discharged into the test pit which had a surface area of about 0.1 acre. Water was recharged during July, August, and September 1941 in several isolated periods varying in duration from a few hours to 3 days. The average rate of infiltration during the test periods was 113 feet per day.

Application of general land flooding, infiltration pits, and recharge wells is briefly discussed.

Horton, R. E.

1905. The drainage of ponds into drilled wells: U. S. Geol. Survey Water-Supply Paper 145, p. 30–39.

The use of wells for drainage of ponds in Jackson County, Mich., is described. The hydraulics and cost of disposal wells are briefly discussed. Typical wells are 3 or 4 inches in diameter and vary in depth from 32 to 213 feet. Not all wells are successful in draining small ponds, many showing a marked decrease in drainage rate after an initial high rate. One measurement indicated a recharge rate of 0.1 cfs in a 4-inch well.

Houk, I. E.

1951. Irrigation engineering, v. 1: New York, John Wiley and Sons, 545 p.

Information on irrigation water losses by percolation and canal seepage is summarized in chapter 12. Methods of artificial recharge of ground water are described (p. 443–446) and several measurements of recharge rates in Los Angeles County, Calif., are tabulated. For efficient economic recharge average rates of 2.0 feet per day are desirable, but some systems have been designed on the basis of 1.0 foot per day. Average rates greater than six feet per day are seldom attained in large areas.

Howson, A. W.

1953. The atomic city water supply: Water Works Eng., v. 106, no. 5, p. 403–404, 482–486.

To increase the water supply for Richland, Wash., artificial recharge of ground water was undertaken in 1948. Surface water from the Yakima Irrigation Ditch and from the Columbia River were recharged into two gravel

pits. Wells drilled on the perimeters of the gravel pits provided the required water supply. Because of porous gravels near the surface in the recharge areas, greater recharge rates were obtained by using a special recharge well. In this well an inverted gravel cone 25 feet in diameter at the surface tapering to 5 feet in diameter at 15 feet below ground surface surrounds a perforated steel casing. About 5 feet below ground surface 6 lines of 12-inch tile project radially and horizontally from the well casing.

Hubner, H.

1954. Die Grundwasseranreicherung in der Letzlinger Heide als Massnahme zur Sicherung der Wasserversorgung Mitteldeutschlands (Ground-water recharge in the Letzlinger Heath as a measure for the protection of the water supply in Central Germany): Wasserwirtschaft-Wassertechnik, v. 4, no. 11, p. 406–417.

This paper presents a comprehensive analysis of the ground-water hydrology of the Letzlinger Heath area north of Magdeburg, Germany. The geology and records of ground-water recharge and discharge are described in detail. It is recommended that increasing water demands from underground storage be met through use of artificial recharge.

Hunt, G. W.

1940. Description and results of operations of the Santa Clara Valley Water Conservation District's project: Am. Geophys. Union Trans., v. 21, pt. 1, p. 13–23.

Water conservation operations by controlled spreading of water in Santa Clara Valley, Calif., are described. Flood waters are stored behind 5 dams and released slowly so that the water is absorbed in stream beds and off-channel ponds. Ponds totaling 4.1 acres in area along Penitencia Creek have shown a recharge rate of 7.3 feet per day during 4 seasons of operation. A percolating pond on the Coyote Creek stream bed is formed by an 8-foot high removable flashboard dam with a concrete base. Recharge rates have varied between 1.36 and 2.04 feet per day. Rates decrease toward the end of each season and under high water-table conditions. Scarifying the bed increases rates. At the junction of Almaden and Guadalupe Creeks a 17-acre pond is formed by long, low, wire-enclosed gravel sausage dams. Recharge rates have averaged 2.7 feet per day. Water diverted from Los Gatos Creek is spread over receptive orchard land and into three ponds. These ponds initially took water at a rate of 3.0 feet per day, decreasing after 3 years to 1.8 feet per day, but increasing to 2.9 feet per day after scraping silt from the pond bottoms.

About one-third of the total annual percolation in the area occurs in percolating works and two-thirds in unimproved stream channels. Conservation operations are estimated to have saved approximately one million dollars in 5 years.

Hutton, G. H.

1914. Water conservation by spreading on gravels: Paper read before the Tri-Counties Reforestation Committee, Riverside, California.

A brief history is given of water spreading along the Santa Ana River in Orange, Riverside, and San Bernardino Counties, Calif.

Imhoff, F.

1947. Besondere Gesichtspunkte bei der Wasserversorgung des rheinisch-westfalischen Industriereviers (Special aspects of the water supply of the Rhine-Westphalia industrial area): Gas- u. Wasserfach, v. 88, no. 3, p. 65–68.

This article presents a summary of water-supply development, distribution, and utilization in the Rhine-Westphalia area of Germany. This area uses water from the Ruhr, Rhine, and Lippe Rivers. Artificial recharge using infiltration basins to purify river waters has been practiced since 1905.

1952. Die Entwicklung der Trinkwasserversorgung im rechtsrheinischen Industriegebiet nach 1945 (The development of the drinking water supply in the Rhine industrial area since 1945): Gas- u. Wasserfach, v. 93, no. 20, p. 569–574.

The expansion of water supplies in the Ruhr area of Germany since 1945 is described. Wide use is made of recharge by infiltration basins, infiltration galleries, and induced infiltration from rivers by means of vertical and horizontal collector wells.

Imhoff, K.

1925. Water supply and sewage disposal in the Ruhr Valley: Eng. News-Rec., v. 94, no. 3, p. 104–106.

Water supplies for cities in the Ruhr Valley, Germany, are obtained from the Ruhr River and are augmented by filter basins fed by the river. These basins extend through the clay of the river valley to gravel, and recharge water to infiltration galleries located in the gravels paralleling the river. Filter basins are built in pairs, contain a layer of sand along the bed, and are cleaned once a year. The recharged water collected in the galleries is fit for immediate consumption, and only in times of very low or very high flows is chlorine added.

1931. Possibilities and limits of the water-sewage-water cycle: Eng. News-Rec., v. 106, no. 22, p. 883–884.

Filter basins for recharging river water to augment ground-water supplies in the Ruhr district of Germany are mentioned.

Institute of Drilling Research.

1950. Diffusion well standards, Long Island area, New York: New York, 4 p.

In order to provide minimum requirements for the construction of diffusion wells for Long Island, N. Y., standards and specifications have been established. The standards are quite detailed and specify criteria for well dimensions, screens, effective area, diffusion-well head, shallow and deep diffusion wells, external casing, positioning conductor line and screen, and observation pipe.

Irwin, J. L.

1931a. Operation of the Pomona Valley Protective Association's spreading grounds, San Antonio Creek, season of 1930–31: Los Angeles, Los Angeles County Flood Control Dist., 10 p.

Percolation measurements were made of natural flows in the San Antonio cone, Los Angeles County, Calif. Rates varied from 0.65 to 14.0 feet per day depending upon the location, discharge, and surface-silt content.

1931b. Report on water sinking experiment in the City of Arcadia well No. 2 Santa Anita Basin: open file rept., Los Angeles, Los Angeles County Flood Control Dist., 6 p.

Water was recharged intermittently for 3 days into a 20-inch 446-foot well at Arcadia, Calif. Caving of the well accompanied recharge on the first day, when rates were as high as 5.88 cfs. Recharge rates of 3.13 cfs on the second day could be continued indefinitely. Nearby pumping wells may have increased the recharge rate, but no attempt was made to observe the effect of the recharging on surrounding water levels.

Jansa, O. V. E.

1950. Alimentation en eau souterraine artificielle en Suède (Artificial recharge of ground water in Sweden) : Technique de l'Eau, no. 42, p. 13–16.

A paper presented earlier (Jansa, 1951b) is summarized.

1951a. Artificial ground-water supplies of Sweden: Internat. Union Geodesy and Geophysics, Brussels, v. 2, p. 227–231; also, 1953: Inst. Hydraulics, Bull. 32, Royal Inst. Technology, Stockholm, 15 p.

In 1897 the first artificial-recharge plant for ground water in Sweden was constructed at Gothenburg. It consisted of 2 infiltration beds having a total area of 1.38 acres by which 8.8 feet per day of raw river water was recharged into glacial sand deposits. Water was pumped for use from wells at distances of 650 to 3,300 feet from the basins and has always been of perfect quality. The plant continues to operate at full capacity (1953).

Since 1937 many towns in Sweden have increased their water supplies by recharging the sand and gravel glacial deposits. Pretreatment of the raw water by rapid sand filtration has been necessary at most localities. Infiltration basins are generally built as high as possible above the water table to enable the infiltrating water to percolate through a large volume of air-filled ground, which is considered to have a biochemical effect on the water. The purifying effect will be increased in this way and there is also the possibility of increasing the supply of oxygen necessary for the breakdown of the organic matter in the raw water by blowing air into the ground. Recharging with soft surface water reduces the hardness of ground water, and contamination of ground water can be counteracted by raising the water table.

At Karlskoga, raw river water is passed through a rapid sand filter plant and recharged through 4 square infiltration basins. Each basin has an area of 0.62 acre, and operates at a capacity of 6.6 feet per day. In the bottom of the basins 33 feet of slow sand filter beds rest on leveled natural gravel. The water table is 49 feet below the bottom of the basin. Recharged water is pumped from six 10-inch wells located about 2,300 feet from the basins.

At Eskilstuna, raw river water is passed through rotating drum screens and rapid sand filters and recharged through 2 rectangular infiltration basins. Each basin has an area of 0.25 acre, and operates at a capacity of about 33 feet per day. In the bottom of the basins 3 feet of slow sand filter beds rest on leveled natural gravel. The recharged water is pumped from wells about 1,000 feet distant.

A similar artificial-recharge plant at Vasteras operates at a recharge rate of 16 feet per day: a plant at Halsingborg operates at a rate of 19 feet per day; and a plant is under construction at Karlstad. Water is recharged through infiltration ditches at Lulea at a rate of 65 feet per day. Owing to the cold climate it is necessary to build the basins as narrow ditches which can easily be covered.

An appendix lists several analyses characteristic of the water from Swedish ground-water recharge works. Quality of raw water is compared with that of ground water.

1951b. Artificial ground-water supplies in Sweden: United Nations Sci. Conf. on Conserv. and Utilization Resources Proc., v. 4, p. 102–104.

Artificial recharge of ground-water supplies is carried out at a considerable number of Swedish municipal waterworks. Because of the quality of Swedish surface water, pretreatment of the raw water by rapid sand filtration has been found necessary at most plants. After such treatment of the raw water the infiltration periods generally will be six months or more. The aim is to locate the infiltration basins as high above the ground-water level as possible in order to get the water to percolate through the greatest possible volume of air-filled ground, such ground being considered to have a biochemical effect. This effect can be increased by blowing air into the ground. In order to obtain complete purification by infiltration, the horizontal distance between the infiltration basins and the wells should be at least 800 feet unless the permeable ground consists of fine sand, in which case this distance should be at least 500 feet.

About 300,000 persons in Sweden are now supplied with artificially recharged ground water, and it is expected that within the next decade this number will increase to about 450,000.

1952. Artificial replenishment of underground water: Internat. Water Supply Assoc., 2d Cong., Paris, 105 p.

Artificial recharge of ground water seems to have been attempted first in 1810 in Glasgow, Scotland, where water was pumped from a filter gallery on an island in the Clyde River. In the early 1820's Toulouse, France, constructed basins near the Garonne River to collect water percolating from the river. Following these early installations, others appeared in France, Germany, Italy, Hungary, United States, and Sweden. The most noteworthy early operation in the United States was the plant built in 1871 at Des Moines, Iowa, in which filter galleries were used.

The new method of supplying water by building infiltration galleries near a lake or river frequently failed because of clogging of the river bed. This led after a time to the use of excavated infiltration basins which could be drained and rinsed when clogged. The first plant of this kind seems to have been built by J. G. Richert in 1897 at Gothenburg, Sweden, and it is still in operation. Several cities in Sweden and Germany now use this method for augmenting water supplies.

A questionnaire requesting information on artificial recharge was sent to several countries. In Australia artificial recharge methods have not yet been practiced; however, investigations have been started to determine the extent to which recharge is possible, and results are promising. In Brazil artificial recharge has not been practiced because of abundant ground-water supplies and impermeable soils. At present in France artificial recharge is used only by the Nancy Water Works although it has been used in other locations in the past and its use is contemplated in the future, particularly in the Seine basin near Paris. In Great Britain recharge has been practiced only at some places. In the London Basin water was recharged into shafts penetrating chalk at average rates of 0.36–0.71 foot per day, based on the chalk contact area. At another location 5.0 cfs was recharged for three winter months. Treated sewage effluent has been infiltrated through permeable strata overlying chalk

at measured rates of 0.30–0.60 foot per day. India reported only one project, a waterworks plant at which water is infiltrated directly into a river bed.

Artificial replenishment was begun in The Netherlands at a plant in Leyden in 1940. Successful experiments have been conducted at Zealand-Flanders and in Enschede, but infiltration wells at The Hague failed. It has been proposed by the Amsterdam Waterworks to bring Rhine River water to the dune area for artificial recharge during periods when the river water is good. In Spain, experimental stream-bed percolation has been practiced in the Llobregat River, and extensive studies have been made of the possibility of augmenting the Barcelona ground-water supply by recharge. At present in Sweden 13 municipal ground-water works are extended by artificial recharge plants. Because surface water is abundant in Sweden and because artifically recharged ground water is of a quality superior to surface water, it is expected that eventually about 25% of the total municipal water consumed will consist of artifically recharged ground water.

An extensive appendix describes artificial-recharge projects at 13 locations in Sweden. From these projects it may be concluded that infiltration basins are constructed as high as possible above the ground-water level, to utilize most effectively the air-filled ground as a filter. Existing plants are all functioning satisfactorily. Infiltration rates range from 3 to 52 feet per day, the average being 33 feet per day. The distance from infiltration basins to pumped wells ranges from 330 to 5,600 feet. A distance of 650 feet is generally considered sufficient for obtaining satisfactory ground water. Infiltration experiments in which recirculated ground water is pumped into temporary basins are often of great value in designing recharge plants.

Four other appendices describe artificial replenishment in the Netherlands (including a general review), recharge at Leyden, infiltration in Zealand-Flanders, and infiltration experiments at Enschede.

1954. Artificial ground-water supplies of Sweden (a second report; Union Géod. Géophys. Internat., Assoc. Internat. Hydrologie Sci. Assemblée Gén. Rome 1954, v. 2, Pub. 37.

In 1954 a total of 17 artificial ground-water recharge installations were in operation, and 10 more were under construction. The total capacity of works in operation is about 73 cfs, and the estimated ultimate total amounts to 163 cfs. Data from these various Swedish projects furnish the following average values:

Height of infiltration basin above ground-water level	26 feet
Effective sand size	0.4 mm
Infiltration rate	20 ft/day
Distance from infiltration basins to pump wells	1,300 feet
Quality of ground water:	
Color, pt	6 ppm
B. coli/100 cm^3	0
Gelatine bacteria/1 cm^3	0

Studies at Eskilstuna using a well penetrating an infiltration basin and a tower containing the filter bed material show that there is a regular gradual decrease in organic matter and oxygen with distance travelled by the recharge water. This purifying effect of the ground is attributed to one or several of the following factors: mechanical filtration, adsorption on the surface of the sand particles, chemical oxidation, and biochemical processes.

Jeffords, R. M.

1945. Recharge to water-bearing formations along the Ohio Valley: Am. Water Works Assoc. Jour., v. 37, no. 2, p. 144–154.

The alluvial deposits of the Ohio valley furnish large supplies to many water systems and industrial plants. Recharge is in part by infiltration from the river and is indicated by the temperature and chemical character of the well water. This recharge is of great importance in some localities. *GAW*

Jennings, J. C.

1950. Disposal of waste cooling water: Am. Water Works Assoc. Jour., v. 42, no. 6, p. 578–582.

One method of disposal of cooling water is use of recharge wells. In Sacramento, Calif., these wells have been rather unsatisfactory, having a tendency to clog up after two to five years of use. Pumping restores capacities to some extent. Recharging warm cooling water gradually raises the temperature of the ground-water supply. This situation has occurred in Sacramento where some well water temperatures rose as much as 20° F. The condition became so serious in Phoenix, Ariz., that a number of supply wells became useless.

Recharge wells and regulations at Fresno, Calif., Long Island, N. Y., and Miami Beach, Fla., are mentioned.

Johnson, A. H.

1948. Ground-water recharge on Long Island; Am. Water Works Assoc. Jour., v. 40, no. 11, p. 1159–1166.

Since 1933, permits for new industrial wells with capacities exceeding 0.15 cfs on Long Island, N. Y., have not been granted unless provision is made for return of the water underground in an uncontaminated condition. Many types of recharge wells were constructed initially; however, experience has shown that wells with 36-inch outer casings, gravel filters, and an inner well screen have been most satisfactory. Wells with screens partially above and below the water table are more successful than those entirely above or below the water table. Over 300 recharge wells are now in operation in the counties of Kings, Queens, Nassau, and Suffolk. Recharge-well capacities range from 0.22 cfs to more than 1.2 cfs. the majority falling in the range of 0.22 to 0.56 cfs. Ground-water temperatures in recharge areas are rising progressively.

Johnson, C. E. *See* Bliss, E. S., 1952 and 1950.

Johnson, Edward E., Inc.

1945. The principal uses of ground water: Johnson Natl. Drillers' Jour., v. 17, no. 6, p. 1–6.

This article is a discussion of the uses of ground water and possibilities of recharging water from municipal supply into wells during the off-peak winter season.

1948. Ground-water resources and their conservation: The construction of water wells: Johnson Natl. Drillers' Jour., v. 20, no. 3, p. 1–4.

Requisite conditions for use and installation of disposal wells are discussed. Recharge wells in Long Island, N. Y., Louisville, Ky., Indianapolis, Ind., and Dayton, Ohio, are mentioned, as well as infiltration galleries along the Mississippi, Platte, and Arkansas Rivers and the shores of Lake Michigan. The applications of pressure relief wells for dams, flood control works, and sand boils are described.

Jones, W. S.

1919. Water spreading as a measure of flood control: Southern California Assoc. Members, Am. Soc. Civil Engineers Bull., v. 1, no. 4, p. 87–91.

Various means of flood control are discussed, including reservoirs, check dams, channel rectification, and water spreading. Water spreading is said to be an effective means of reducing floods, and experience on San Antonio cone and the underlying conditions are cited. Conservation measures were started in 1895, and in 1917, 180 cfs were led from the dam into two or three ditches. Less than one cfs reached a return ditch one mile away. The value of undisturbed vegetation in water spreading is pointed out. The author advocates breaking main channel into many smaller channels in which water spreading may be extremely effective. Similar methods in the San Gabriel, Los Angeles, San Dimas, Big and Little Dalton, Santa Anita, and other rivers are suggested for purposes of reducing floods. *FHK*

Jordan, L. W. *See also* Hofmann, O. D., 1936; Laverty, F. B., 1951.

1931a. Percolation under proposed improved channel conditions in Big and Little Dalton, San Dimas and Walnut Washes below Covina Canal: open-file report, Los Angeles, Los Angeles County Flood Control Dist., 3 p.

In Big Dalton Wash, Los Angeles County, Calif., the percolation rate was 10.7 feet per day shortly after the channel had been plowed. Two measurements in the same section the following year were 3.9 and 2.9 feet per day.

1931b. Water sinking experiment in the Charnock Plant well no. 1: open file rept., Los Angeles, Los Angeles County Flood Control Dist., 4 p.

Water was admitted into a 20-inch 394-foot well. A maximum rate of 0.97 cfs was successfully maintained for 48 hours, the water level in the well remaining constant throughout. After cutting the inflow to 0.54 cfs, the head dropped 44 feet to an equilibrium level after several hours. Because of casing obstructions and silt introduced around the well during construction, it is believed that this test does not represent the absorptive capacity of the deeper gravels.

1931c. Water sinking experiment in the Sentry Plant well no. 3: open file rept., Los Angeles, Los Angeles County Flood Control Dist., 4 p.

Water was admitted to an abandoned 14-inch well 279 feet deep while a well 25 feet away was being pumped. Approximately 0.5 cfs was recharged for 4 hours, then increased to 1.0 cfs for 20 minutes, and then discontinued because of sand in the water. In the last 20 minutes the water in the recharge well suddenly lowered, causing a rise in the pumping well. This, together with the turbid discharge water, indicates a breaking through of a channel between the two wells. After shutting off the flow into the test well, gravel was heard to cave in around the casing.

1936. Report on spreading grounds on Rio Hondo and San Gabriel River below Whittier Narrows: Los Angeles, Los Angeles County Flood Control Dist., 56 p.

This report describes experiments on water spreading in small test basins in Los Angeles County, Calif., near the Rio Hondo and San Gabriel Rivers. Final percolation rates were 4.0–4.3 feet per day in loam soil, 10.0–12.5 feet per day in sandy soil, and 3.0 feet per day in the underlying sandy silt. These rates were derived from observed rates in various experimental plots by reduction for silt content, by conversion of short term rates for 7–10 days to long-term

rates, and correction for marginal fringe. It was found that the recharge rate varies with the ratio of perimeter to area, this marginal fringe effect being most important for small elongated basins and least important for large basins commonly used in spreading practice.

1937a. (and Luce, J. W.). Report on investigation of Pacoima spreading grounds, 1936-1937: 41 p., Los Angeles, Los Angeles County Flood Control Dist.

Spreading tests were made below Pacoima Dam in San Fernando Valley, Calif., on basins denuded of vegetation, basins with thick cover of native vegetation, furrows, and ditches. In furrows, in a 14-day test in which 24 percent of the gross area was wetted, the initial rate was 10.2 feet per day, the final rate was 3.4 feet per day, and the average rate was 7.5 feet per day. In denuded and cultivated basins, in a 15-day test in which 71 percent of the gross area was wetted, the initial rate was 6.1 feet per day, the final rate was 2.6 feet per day, and the average rate was 3.9 feet per day. In native vegetation basins in which 71 percent of the gross area was wetted, initial rates ranged from 4.2–7.7 feet per day, final rates (after 6–17 days) were 3.0–6.3 feet per day, and average rates were 4.4–5.6 feet per day. In a denuded and uncultivated basin in which 71 percent of gross area was wetted, the initial rates were 2.3–3.7 feet per day, final rates (after 5–6 days) were 1.9–3.1 feet per day, and the average rate was 2.7 feet per day.

Furrows and ditches are not recommended for spreading because of the smaller percentage of wetted area and because the surface storage space is smaller than that of basins. It is recommended that basins be built without clearing off the vegetation. Spreading rates assumed for design from spreading tests are 6 feet per day initially and 2 feet per day as a minimum.

1937b. (and Reber, A. W., and Thayer, W. N.). 1936-37 report on San Antonio spreading grounds investigation: Los Angeles, Los Angeles County Flood Control Dist., 43 p.

A report on spreading studies along San Antonio Creek, Los Angeles County, Calif., is presented. Conclusions are (1) that checks placed in canals and gullies are aids to percolation in that they retard erosion of the channel beds, increase the wetted area, and entrap sand and gravel transported from the creek bed; (2) that loose rock checks are less expensive to build than other types and will withstand flows as high as 2 cfs per foot of crest length; (3) that rubble masonry checks are best for larger flows; and (4) that scarifying canal beds by shooting with dynamite is effective in causing high percolation rates for initial flows.

Spreading capacities are based on the following recharge rates:

Area	Initial rate (feet per day)	Continuous use (feet per day)
Canals with checks and scarified	26.4	13.2
Canals with checks only	11.8	8.8
Canals unimproved	6.2	6.2
Basin areas	8.9	8.9
Terminal areas	5.9	5.9

1937c. (and Thayer, W. N.). Preliminary report on the practicability of spreading water on Tujunga Wash: Los Angeles, Los Angeles County Flood Control Dist., 21 p.

This report covers the necessity and practicability of water-spreading along Tujunga Creek, Los Angeles County, Calif., and the requirements of permanent spreading development. It is concluded that channel scarification would reduce excess channel flows and prevent them entirely if runoff does not exceed 300 cfs; that spreading is practicable but of questionable justification as a temporary measure; and that capacity is available for spreading as much as 1200 cfs. A percolation rate of 6 feet per day and a 70 percent coverage of gross area were assumed. Spreading ground construction costs are estimated to be $350 per acre.

1938. Report on the San Antonio spreading grounds investigation for the 1937-38 season: Los Angeles, Los Angeles County Flood Control Dist., 31 p.

A seasonal report of spreading along San Antonio Creek, Los Angeles County, Calif., is presented. Conclusions deal primarily with operating practices and facilities. Erosion during a flood temporarily increased percolating capacities 200 percent in the creek channel but decreased canal rates by 60-70 percent because of silt deposition. Recharge rates in wash channels are estimated to be 2.2 feet per day.

1939. (and Keim, P. F., and Thayer, W. N.). Report on spreading grounds below Whittier Narrows, Rio Hondo spreading operations, 1938: Los Angeles, Los Angeles County Flood Control Dist., 50 p.

As part of the investigations for development of spreading grounds below Whittier Narrows, Los Angeles County, Calif., spreading tests were conducted. In three basins the measured average initial percolation rate was 18 feet per day, the rate decreasing to 4 feet per day after three days, and declining to 1.8 feet per day in the succeeding 20.3 days. Dewatering one of the basins caused an increase in adjacent percolation rates, and refilling correspondingly reduced the rate. The average rates were 2.4 feet per day for the season and 1.6 feet per day when drying periods were included. Observations of the water table showed that it rose rapidly beneath the basins, that the percolation rate decreased as the water table approached the bottom of the basins, and that the decrease was more gradual with the flattening of the side slopes of the ground water mound. Scarification increased recharge rates when the mound was beneath the basin, but had no effect when the water table was in contact with the basin.

When the depth of water in one basin was lowered from 3.3 feet to 2.0 feet, the recharge rate decreased from 2.56 to 2.02 feet per day. During this period the ground-water mound was in contact with the water in the basin. It is believed the effect would be less if the surface and subsurface water were not in contact. Because of thin clay strata interspersed in the sands and gravels of the aquifer, a saturated lens was built up on these strata before the ground-water mound formed upon the water table. Eventually the true mound formed, merged with the saturated lens and established its ultimate gradient. The greatest volume of recharge water moved in the direction of the normal water-table slope.

A detailed analysis of the costs and economics of water spreading is included. Unit cost for the year's operation was $1.13 per acre-foot of water.

1940. (and Thayer, W. N.). Report on the San Gabriel coastal plain spreading test of 1939: Los Angeles, Los Angeles County Flood Control Dist., 73 p.

Tests on spreading along the San Gabriel River, Los Angeles County, Calif., were made to obtain data on economics and area needed for ultimate

development of off-channel spreading. Water was spread in 8 basins divided into 4 areal groups. Mean group recharge rates were 2.1, 0.6, 1.1, and 4.0 feet per day. The first is low because of a high ground-water table, the second and third because of the presence of a subsurface clay lens. The unit capacity for the overall area is 2.1 feet per day when 80 percent of the gross area is wetted.

Costs and economics of water spreading are analyzed. Unit cost for the year's operation was $1.83 per acre-foot of water.

1949. (and Koch, E. J. Jr., and Stone, R.). Final report on sewage reclamation spreading test adjacent to Whittier sewage treatment plant: Los Angeles, Los Angeles County Flood Control Dist., 43 p.

This report describes field tests to determine feasibility of spreading sewage plant effluents. Spreading rates on sands in the Rio Hondo Coastal Basin spreading grounds, Calif., were 1.5 feet per day initially, decreasing to 0.5 foot per day after 7–9 days, and averaging 1.0 foot per day. The recommended procedure consists of continuous spreading for 7 days alternating with 7-day rest periods for drying and cultivating the basins. A spreading area of 80 acres will be required for a capacity of 20 cfs, and 300 acres for 75 cfs. During the tests no odors were detected even from unchlorinated effluent running for 7 days. Water in the test basin had only a slight tinge of grayish turbidity, and samples of percolated effluent were clear. Bacteriological analysis of water samples collected 4–7 feet below the test basin indicated that there is no danger of polluting ground water by spreading the unchlorinated secondary effluents tested.

1950. (and van der Goot, H. A.). Sewage reclamation spreading test adjacent to Azusa Sewage Treatment Plant: Los Angeles, Los Angeles County Flood Control Dist., 33 p.

Experimental tests of spreading sewage effluent at Azusa, Calif., from May to September 1949 are reported. Spreading of primary effluent having a B.O.D. (biological oxygen demand) in excess of 80 ppm rapidly produced anaerobic conditions in the test basin. Aerobic conditions were maintained in treated sewage having an initial B.O.D. of 30 ppm at a percolation rate of 1.2 feet per day. The percolated fluid was of satisfactory quality at the 7-foot level as long as aerobic conditions were maintained in the test basins. No odors developed under aerobic conditions. Pond temperatures ranged from 67° to 89° F. Algae formed in the ponds, but their unsightly appearance was outweighed by their usefulness in producing oxygen. It is possible, but quite costly, to reestablish aerobic conditions in a spreading basin once anaerobisis has set in. A satisfactory operating cycle consists of at least one month's spreading followed by a rehabilitation period of variable length, probably not exceeding one week.

Kazmann, R. G. *See also* Engler, K., 1945.

1946a. Induced infiltration supplies most productive well field: Civil Eng. v. 16, no. 12, p. 544–546.

Ranney water collector system of six collectors at Wabash River Ordnance Works, Ind., derives most of its water by induced infiltration from the Wabash River. Average pumpage from August 1943 through July 1945 was 112 cfs; maximum pumpage on September 28, 1943, was 138 cfs. *FHK*

1946b. Notes on determining the effective distance to a line of recharge: Am. Geophys. Union Trans., v. 27, no. 6, p. 854–859.

This article describes a technique for determining the effective distance of a well from a surface water supply by the drawdown measured in a single observation well and the duration of pumpage.

1948a. Factors involved in water supply by river infiltration: Am. City, v. 63, no. 2, p. 103.

A series of questions and answers pertaining to induced recharge by river infiltration are listed.

1948b. River infiltration as a source of ground-water supply: Am. Soc. Civil Engineers Trans., v. 113, p. 404–424.

The characteristics of a ground-water supply based on the infiltration of water from a nearby stream are discussed. The effect of changes in river stage as well as changes in river temperature on well-field yields, drawdowns, and water temperatures, is revealed through the data presented. The absence of pathogenic bacteria from the ground water despite the contamination in the source water is shown. A method is described for testing a well field of horizontal collectors to determine the firm yield of the field under the worst possible conditions of river stage and temperature. The construction of a horizontal collector is described and the production record and operating characteristics of a field of seven such units are given in detail. The paper is based on more than four years of observation of the water supply of the Indiana Ordnance Works near Charlestown, Ind.

1948c. The induced infiltration of river water to wells: Am. Geophys. Union Trans., v. 29, no. 1, p. 85–89.

Two methods are proposed for determining whether surface water will infiltrate to an adjacent aquifer if wells are pumped at the site tested. One method is based on steady flow before the onset of pumping, whereas the other is based on steady flow during a pumping test. Both methods rely on contour maps of the piezometric surface or changes in the piezometric surface. The maximum rate of infiltration is not determined, only whether infiltration will occur after pumping begins. The analysis gives a method of determining the effective distance to a line of recharge.

1949. The utilization of induced stream infiltration and natural aquifer storage at Canton, Ohio: Econ. Geology, v. 44, p. 514–524.

An account is given of designing a water system to develop 15 cfs for Canton, Ohio, involving three wells, two of which are dual-purpose for recharging and production. *NR*

1950. Ground-water storage and recharge: Public Works, v. 81, no. 2, p. 45–46.

Radial collector wells at Canton, Ohio, recharge a lower aquifer used for city water supply from a shallow upper aquifer which has natural recharge from a stream bed. *GWS*

Keim, P. F. *See* Jordan, L. W., 1939.

Keller, G.

1933. Grundwassersperren (Ground-water barriers) : Bautechnik, v. 11, no. 21, p. 270–272

Subsurface cutoff walls for damming ground water are described. Such barriers have been constructed of a variety of materials, including clay, concrete, wood, and iron. Sketches of several designs are presented. Most structures extend below ground to relatively impermeable strata and a few feet above ground. When properly located with regard to the surrounding topography, these barriers can pond excess surface waters and promote additional ground-water recharge. Wells are frequently located immediately upstream from the structure to tap the subsurface water storage. Several structures in central Africa are described and illustrated.

1939. Über Anteilswerte von uferfiltriertem Flusswasser und Grundwasser im Forderwasser (On the partial values of bank-filtered river water and ground water in water supply) : Prakt. Geologie Zeitschr., v. 47, no. 12, p. 199–202.

This article describes the geologic and hydrologic conditions under which wells may pump effectively both ground water and induced recharge water from a nearby stream. An example of the combined development is the water works at Kettwig, Germany, where the water pumped is in part induced recharge from the Ruhr River.

Kent, L. E.

1954. Artificial recharge of ground water in the Union of South Africa: Union South Africa, Geol. Survey, duplicated report, 9 p.

Artificial recharge is being practiced to a limited extent in the Union of South Africa. At Fraserburg an earth dam was built to trap intermittent surface flows and recharge ground water. Improved yields of the town's wells, which are located alongside the dam, justify the construction. Similar dams have and are being constructed in other locations.

Soil conservation practices have reduced surface runoff and increased infiltration to ground water. No specific data are available, but where the practices are effective, increased well yields, larger springs, and higher water tables are noticeable.

Higher water tables and larger stream flows have resulted from recharge from irrigation in several areas. Many cities spread treated sewage effluent. Near some of these sewage farms waterlogging has resulted from the increased ground-water recharge.

Kihm

1932. Die Wasserversorgung des Ruhrkohlengebiets vom Rheine her (The water supply of the Ruhr area from the Rhine) : Gas- u. Wasserfach, v. 75, no. 29, p. 586–592.

In the development and plan of water supply in the Ruhr Basin wells and infiltration galleries furnish water by induced infiltration from the Rhine River.

Kingsbury, F. H.

1936. Public ground-water supplies in Massachusetts: New England Water Works Assoc. Jour., v. 50, no. 2, p. 149–196.

In describing various types of ground-water supplies in Massachusetts, two are mentioned and illustrated which involve artificial recharge. They include

systems of underdrains installed parallel to a river beneath spreading basins and open filter basins.

Klaer, F. H., Jr.

1948a. (and Guyton, W. F., and Todd, D. K.). A preliminary list of references pertaining to artificial recharge of ground water in the United States: U. S. Geol. Survey open-file report (mimeo.), 35 p.

As a part of a cooperative research project by the Indiana Department of Conservation, Purdue University, and the U. S. Geological Survey, a list of 196 references relating to artificial recharge is assembled. Artificial recharge is defined and classified, and localities where artificial recharge is or was in use are listed by states.

1948b. (and Thompson, D. G.). Ground-water resources of the Cincinnati area, Butler and Hamilton Counties, Ohio: U. S. Geol. Survey Water-Supply Paper 999, 168 p.

Various methods of artificial recharge and the possibility of their application to increase ground-water supplies in Mill Creek Valley, Ohio, are briefly described. Spreading by basins appears to be feasible in certain locations; however, an adequate surface-water supply must be available for recharge, and field experiments in promising areas should be conducted before any large artificial recharge operation is installed.

1949. Artificial recharge of ground water in the United States: Paper presented at annual meeting of Missouri Water and Sewerage Conf., Joplin, Sept. 26, 1949.

This paper presents a general discussion of concept of recharge, and definition and classification of artificial recharge.

1951. Artificial recharge of aquifers: Union Internat. Géod. Géophys. Assoc., Internat. Hydrologie Sci. Assemblée Gén., Brussels 1951, v. 2, p. 135.

Artificial recharge is briefly defined.

1953. Providing large industrial water supplies by induced infiltration: Mining Eng., v. 5, no. 6, p. 620–624.

Water supplies dependent upon induced infiltration can be developed by vertical wells, by infiltration galleries, or by horizontal water collectors. Each method is described, and the advantages of obtaining water by induced infiltration with respect to cost, chemical quality, and temperature are shown by examples of specific water supplies.

Koch, E. J., Jr. *See* Jordan, L. W., 1949.

Konig, A.

1930. (and Bruns, H.). Künstliche Grundwasser-Anreicherung unter Berücksichtigung der Verhältnisse des Ruhrkohlengebiets (Artificial ground-water recharge with regard to the situation of the Ruhr coal area): Gesundheits-Ingenieur, v. 53, no. 43, p. 662–667, no. 46, p. 740–745.

This article describes artificial recharge installations for water supply bordering the Ruhr and Lippe Rivers in Germany. Typical installations are long, narrow recharge basins fed by river water. Basin slopes are 1:1 and are concrete-lined. The recharged water is collected by infiltration galleries or

lines of wells located between the basins and the river so as to obtain water from both sources. Plant layout and water-supply operations are described in detail, and geologic cross sections are included.

Kramsky, M.

1952. Utilization and artificial replenishment of ground-water reservoirs: Los Angeles, Southern California Univ. Masters Thesis, 154 p.

This thesis presents a comprehensive review of the various methods and applications of artificial recharge. Recharge projects in the South Coastal Basin of California; Long Island, N. Y.; New Jersey; Des Moines, Iowa; Bountiful, Utah; and Louisville, Ky., are described.

Kretsinger, R. *See* Banks, H. O., 1954.

Kring, H.

1931. Wasserwerk Ackerfähre an der Ruhr der Gutehoffnungshutte Oberhausen AG., Oberhausen (Rheinland), mit Schnellfilteranlage und Versickerung zur Anreicherung des Grundwassers (Ackerfähre waterworks on the Ruhr of the Gutehoffnungshutte Oberhausen Company with rapid sand filters and percolation for ground-water recharge); Gas - u. Wasserfach, v. 74, no. 9, p. 193–199.

The plant design and layout of the Ackerfahre waterworks bordering the Ruhr River and the Rhine-Herne Canal in Germany is described. Raw water is taken from the Ruhr, passed through rapid sand filters, and recharged underground through filter basins. Bottoms of the basins contain four feet of graded sand. The recharged water is pumped from a series of nearby wells for use, and in another portion of the installation wells collect water by induced infiltration from the two surface-water sources.

Kruegel, J.

1948. How Kirkwood's radial water collector works: Am. City, v. 63, no. 10, p. 108–109.

Ranney water collector at Kirkwood, Mo., obtains water by induced infiltration from Meramec River. Estimated capacity is about 12 cfs. *FHK*

Krul, W. F. J. M.

1946. (and Liefrinck, F. A.). Recent ground-water investigations in the Netherlands: New York, Elsevier Publishing Co., 78 p.

Chapter 3, Groundwater Replenishment, mentions that a number of waterworks in Europe have established wells in permeable strata along riverbanks, where river water can readily infiltrate. Artificial recharge was first developed in 1898 at Goteborg, Sweden, by using ditches. Many German cities, including Frankfort-on-Main, Wiesbaden, Hamburg, Dresden, and several in the Ruhr district, have since followed suit. Recharge by wells was practiced in the city of Paderborn, Germany.

Recharge through infiltration wells was attempted near the river Lek. Reresults were unsuccessful because of rapid clogging and because of eruptions along the well casing caused by increased pressure around the outside of the well. Clogging may result from suspended matter, from iron oxide in solution, or from oxygen content of the water.

Definite plans and designs have been prepared for a proposed supplemental water supply for Amsterdam. This involves the transportation of Rhine River

water through a ship canal to a point where it is pumped into large storage reservoirs, thence filtered and treated as required, and finally pumped into infiltration canals in the Amsterdam dune area. The water will infiltrate into the dunes and be collected at lower levels by drainage canals for water-supply purposes. Recharging will proceed only during those portions of the year in which the river water salt content is sufficiently low. It is estimated that in a future normal year about 40 percent of the water supply may be obtained from this recharge system. Model studies of the proposal utilizing glass-plate models which simulate the various recharge and discharge conditions are under way.

As a part of the waterworks system of Leyden, artificial recharge of dunes by means of canals has been practiced for several years. Deep wells near the canals pump the recharged water for use. Based upon experiments and experience elsewhere, a recharge rate of 1.2 feet per day was chosen for design purposes. Because recharge water is available during only 4 months of the year and water requirements vary throughout the year, an unsteady ground-water distribution results. The problem was investigated by analytical studies, by use of models, and by water-table observations. Recharge rates were initially 1.0 to 1.3 feet per day, but they increased to 1.9 feet per day as the air contained in the sand was removed. Intermittent infiltration allowed silt collecting in the bottoms of ditches to dry and partially blow away. Entry of air permitted retained organic matter to break up so that satisfactory recharge rates could be maintained. Water quality was improved by recharging; temperature differences between ground water and recharge water disappeared at a distance of 130 feet.

Lane, D. A.

1934a. Increasing storage by water spreading: Am. Water Works Assoc. Jour., v. 26, no. 4, p. 421–429.

Test basins for water spreading were constructed and tested for 2 years in San Fernando Valley, Calif. Recharge rates varied from 3.0 to 10.0 feet per day. Over a 33-day period the average rate was 6.29 feet per day, and for a 53-day period, 3.86 feet per day. A mean rate of 2.0 feet per day is a safe basis for estimating operation of major spreading grounds. Water-table elevations correlated with spreading rates and showed a 5-day lag.

On the basis of these spreading tests, a large spreading area was constructed in Big Tujunga Wash. Basins were cleared and strippings were used to form dikes between basins. The completed cost per acre of the gross area in operation came to $1,269. Water depths in basins are maintained at 0.5 foot to prevent wave action from cutting side walls. Basin bottoms are cultivated with a springtooth harrow, the ridges and furrows thus made having a difference in elevation of 0.20 to 0.30 foot. Silt stirred by wave action settles to the bottom of each furrow, leaving ridges free. Average seasonal recharge rates ranged from 6.15 to 6.92 feet per day. Recharge rates were found to be related to monthly temperatures. Spreading costs averaged $0.66 per acre-foot, and total annual charges for pumped recharge water equaled $3.36 per acre-foot.

Water is spread also in abandoned gravel pits. One pit showed a recharge rate of 24 feet per day for a 30-day period.

1934b. Surface spreading-operations by the basin-method and tests on underground spreading by means of wells: Am. Geophys. Union Trans., v. 15, pt. II, p. 523–527.

Spreading basins have been established in San Fernando Valley, Calif., to utilize the ground-water basin as a storage regulator for Owens River Aqueduct

water. Basins average 100 by 400 by 3 feet and cover a net area of 47 acres. Water depths are maintained at 0.50 foot. Experiments revealed that percolation rates can be maintained by cultivating with a springtooth harrow, the teeth set at a depth sufficient to form ridges so that silt crusts are broken up and silt removal is unnecessary. Basins may be operated for 10 to 15 days between cultivations and the percolation rate maintained at nearly the maximum. A drying period of 3 days before cultivation is allowed during the winter, and reduced to less than 1 day in spring. Cultivation by tractor requires 15 minutes per basin. Over 3 years the seasonal average recharging rate was 6.19 feet per day.

Several experiments on recharge through wells have also been conducted. In one group of 20-inch wells located in San Fernando Valley and penetrating granitic alluvium to an average depth of 400 feet, results were unsatisfactory. The wells initially took considerable water, but the percolation rate decreased so rapidly that after one week the method was discontinued. To put the wells back in operation required redevelopment.. The sealing-off effect is attributed to the forcing of small loosened soil particles into the interstices of the surrounding aquifer. In a 16-inch well located in southeastern Los Angeles, an average recharge rate of 0.26 cfs was maintained for 92 days. This well is 300 feet deep and is perforated at three zones totaling 35 feet in thickness. A head of approximately 65 feet was maintained above the natural water table. The effect of head on recharge was studied in a well in southwestern Los Angeles. The well is 16 inches in diameter, 625 feet deep, and is perforated in 4 zones totaling 156 feet. Starting with a 10-foot head above static water level, the head was increased by 5-foot intervals to a maximum of 72 feet. The recharge rate was nearly a linear function of head, increasing from 0.13 cfs for a 10-foot head to 0.33 cfs for a 70-foot head. Important factors are: water must be clear and free from matter which would promote growth of bacteria; percolation rates depend upon applied head; and position of casing perforations, whether opposite a dry stratum or one containing water. Frequent surging of a well will materially increase the percolation rate.

1936a. Artificial ground water: Eng. News-Rec., v. 116, no. 22, p. 779–780.

The Tujunga spreading grounds in San Fernando Valley, Los Angeles County, Calif., and their operation over the last five years are described. The spreading area is divided into basins averaging 100 by 400 feet in size and separated by dikes 4 feet high and 15 feet wide at the base. Flow into the basins is through a 6-inch pipe containing a valve adjusted to maintain an average water depth of 6 inches in each basin. Before admitting water to a basin the bottom is cultivated with a springtooth, tractor-drawn harrow. Percolation rates immediately after harrowing may be as high as 10 feet per day, but this rate decreases to about 3 feet per day if operation at the basin is continued without interruption for long periods. Harrowing the basin at about 10-day intervals gives best results. Time required for drying out and harrowing a basin varies from 8 to 24 hours, depending upon weather conditions. Average seasonal recharge rates in the 5 years of operation range from 5.51 to 6.92 feet per day. The lowest rate occurred in 1934 as a result of spreading silty water from the flood of January 1, 1934.

By means of observations in key wells it has been possible to follow the underground movement of recharged water for several miles.

1936b. Artificial storing of ground water by spreading: Am. Water Works Assoc. Jour., v. 28, no. 9, p. 1240–1251.

Storage, cost, value, location, water rights, and methods of water spreading are discussed in general terms. Recharge rates in various southern California stream channels range from 2.74 to 16 feet per day for short periods and over small areas. A clean cultivated basin has produced a 4-year average of 6.20 feet per day. Initial rates may be five times as great as normal rates and may last for only a few days.

1936c. Transforming surface water into underground storage: Water Works Eng., v. 89, no. 18, p. 1136–1139.

This article contains a general discussion of water spreading with particular reference to southern California. Locations of spreading areas, legal aspects, and various spreading methods are briefly described. Stream-channel spreading is widely practiced in southern California to conserve and to distribute water, and in some instances to reduce flood peaks. Unit spreading rates ranging from 2.74 to 16 feet per day in stream channels, and 5.51 to 6.92 feet per day for a spreading basin are mentioned. In all areas the initial rate may be five times as great as the normal percolating rate. This initial rate decreases within a few days to the normal rate.

Larson, F. D. *See* Stokes, C. M., 1954.

Larson, T. E. *See* Horberg, L., 1950.

Lauenstein, J.

1932. Das neue Wasserwerk der Stadt Paderborn (The new waterworks of the City of Paderborn) : Gas- u. Wasserfach, v. 75, no. 5, p. 81–87.

The historical development of the water supply for Paderborn, Germany, is described. The present waterworks recharges surface water underground through long lines of filter basins. A line of wells located about 140 feet from the basins collects the water for use by the city.

Laverty, F. B.

1946. Correlating flood control and water supply, Los Angeles coastal plain: Am. Soc. Civil Engineers Trans., v. 111, p. 1127–1158.

More than 2,000 acres of water-spreading grounds have been developed in Los Angeles County, Calif., using the methods of ditch and furrow, basin, and regulation of flows in stream channels. The ditch and furrow method is generally used in rough or sloping terrain. Canals and ditches are laid out roughly on the topographic contour with sufficient slope to prevent deposit of suspended material. A modification of this method is to install broad, shallow main canals, from which smaller ditches at regular intervals spread the water over the area. Advantages of the ditch method are the low costs of maintenance and operation; an objection is the very low percentage, usually not more than 10 to 12 percent, of the total spreading grounds in direct contact with water. The comparable figure for basins is 75 to 80 percent. The basin method involves the construction of dikes or small dams at regular intervals across abandoned natural channels. Water is led into the upper basin by canal and spilled from basin to basin. From the last basin the waste water is returned to the flood channel. The basin method is widely used because of its economic use of land. Stream-channel spreading represents an effort to distribute a narrow flowing stream over a wide channel. Cultivators, plows, and furrowing machines are used to widen the wetted channel and break the silt seal. The method is widely used on streams in southern California which are subject to flash flows of short duration but high rate.

In selecting spreading grounds, promising areas are checked by test holes to depths of 30 feet or more to reveal the presence of clay lenses or other soil conditions which would seriously affect long-time spreading rates. Also investigated are existing streamflow percolation rates and the desired quantity of water for spreading. Often small sample basins are tested for a period of several weeks to obtain further data on percolation rates.

An initial 40-acre spreading ground in the Rio Hondo Coastal Basin was constructed in 1938. The estimated cost of spreading, including wooden water-control structures, interest, maintenance, and operation, was $5.00 per acre-foot of the water spread. If several hundred acres were developed, the cost might be as little as $3.00 per acre-foot.

Recharge rates measured in the spreading areas in the Rio Hondo and San Gabriel Coastal Basin have varied from initial values of 7.9 feet per day to final values of 1.8 feet per day. When the water table is less than 20 to 25 feet below the surface, a ground-water mound quickly builds to the surface under spreading areas. This reduces the recharge rate and emphasizes the importance of the depth to the water table.

Data on recharge rates from several spreading grounds are presented in tabular form. Maximum rates range from 3.0 to 14.9 feet per day, while minimum rates extend from 1.4 to 7.5 feet per day.

1951. (and Jordan, L. W., and van der Goot, H. A.). Report on tests for the creation of fresh water barriers to prevent salinity intrusion performed in West Coastal Basin, Los Angeles County, California: Los Angeles, Los Angeles County Flood Control Dist., 70 p.

Various methods of ground-water recharge have been tested by Los Angeles County Flood Control District in terms of their feasibility for controlling sea-water intrusion. Pertinent test results are summarized below.

At Manhattan Beach, Calif., tests on a recharge well showed that bacterial slimes will form and clog an aquifer being recharged unless flows are sterilized; that slimes can be controlled by dosing recharge water initially with 15 ppm chlorine; that chlorine dosages should be commenced immediately upon recharge to sterilize potential bacterial growth sources; that clogging by incrustations of insoluble carbonates did not occur; that it is desirable to exclude air from recharge flows; that the recharge well carried a flow of between 1 and 2 cfs for a five-month period; and that pressure elevations created by recharging are approximately proportional to the recharge rate.

A series of water-spreading tests was performed at Redondo Beach, Calif. The tests indicated that percolation rates can be maintained at 4 to 6 feet per day, that growth of soil-clogging micro-organisms can be controlled by a chlorine concentration of 3 ppm, and that spreading was not feasible in areas where impervious clay strata overlay the main aquifer.

Well-recharge tests at El Segundo, Calif., led to the conclusions that adequate percolation capacity into a confined aquifer in the sand-dune area can be developed by means of pit-type injection wells drilled in basins or trenches and filled with pea gravel; that these wells should be 30 inches in diameter, at least 40 feet deep, and should be spaced a minimum of 20 feet apart; that gravel filters must be sterilized intermittently with copper sulfate, calcium hypochlorite, or other similar compounds to prevent clogging by algae or bacterial slimes; that gravel-filled pit-type wells cannot be cleaned when percolating

capacity is lost; that an 18-inch pipe extending down into the well would permit redevelopment by pumping or surging; that wells of this type cost about $2.00 per foot to construct exclusive of overhead; and that recharge water has no effect on confined aquifers below the aquifer receiving recharge water.

1952a. Ground water recharge: Am. Water Works Assoc. Jour., v. 44, no. 8, p. 677–681.

A general discussion of ground-water recharge with particular reference to southern California is presented. Recharge rates by spreading vary from 1.0 foot per day under unfavorable conditions to 10 to 16 feet per day under favorable ones. Current total spreading costs average $2.00 to $8.00 per acre-foot, depending upon the cost of land.

Tests of 12- to 16-inch-diameter recharge wells have indicated that flows of 0.4 to 2.0 cfs with 15 ppm of chlorination may be injected continuously for a month or more before redevelopment becomes necessary. Costs for installation, redevelopment, injection, and treatment may total $15.00 to $25.00 per acre-foot, hence this method is useful only where the value of water is high or where a secondary value is to be achieved.

Tests of spreading sewage treatment plant effluent have shown that recharge rates of 1.0 foot per day are feasible in coarse gravel where depths to the water table exceed 10 feet. Sewage reclamation costs, including treatment plants and spreading grounds, are estimated to be $12,00 to $16.00 per acre-foot over a 40-50-year financing period.

1952b. Recharging wells expected to stem sea-water intrusion: Civil Eng., v. 22, no. 5, p. 313–315.

One method of controlling sea-water intrusion underground is by injecting fresh water through a line of recharge wells paralleling the coast. Experimental study of this method by use of a recharge well at Manhattan Beach, Calif., was conducted by the Los Angeles County Flood Control District. The test well had a 16-inch perforated casing set 230 to 260 feet below ground surface in sandy gravel. Two clay layers totaling 31 feet in thickness overlie the confined aquifer. The well was recharged from May to October 1950. The most significant data and conclusions of the recharge tests are: (a) that it seems practical to recharge a well under these conditions at the rate of above 1 cfs for several months, without cleaning the well by surging or pumping, if the water is treated with 15 ppm of chlorine to kill bacteria that produce pore-clogging slimes; (b) that recharge water moved inland at the rate of 8 feet per day; (c) that the height of the pressure mound was proportional to the input rate; and (d) that a well spacing of 500 feet will create a continuous recharge mound to resist sea-water intrusion.

1954. Water-spreading operations in the San Gabriel Valley: Am. Water Works Assoc. Jour., v. 46, no. 2, p. 112–122.

This paper describes the history and development of water-spreading grounds in San Gabriel Valley, Los Angeles County, Calif. Several natural and artificial spreading areas have been established in the last 40 years to conserve floodwaters. Capital investment and operating costs for spreading grounds of 150 acres and larger do not exceed $8 per acre-foot of floodwaters conserved. If the development costs of the grounds are assigned to the initial purpose of floodwater conservation, then the total spreading cost for conservation of imported waters will not exceed $3 to $4 per acre-foot.

Lazenby, A. J.

1938. Experimental water-spreading for ground-water storage in Salt Lake Valley, Utah, 1936: Am. Geophys. Union Trans., v. 19, pt. 1, p. 402–412.

A series of water spreading tests was run near Salt Lake City, Utah, to determine the feasibility of the method for ground-water recharge. In the first test about 4 cfs of water was allowed to flow into an abandoned reservoir for 31 days. A rise in the water table was measured over an area of about 400 acres, the maximum rise being 7.58 feet. For the second test about 6 cfs of water was allowed to flow for 35 days into an old gravel pit. During the recharge period water rose steadily in the pit. Observation wells were so far away that no changes in water levels could be detected. The final test consisted of a series of measurements of seepage losses from an old unlined canal. Weirs were installed for measurement, and flows averaging 4.1 cfs were released into the canal. The losses in the canal were found to be surprisingly large, amounting to 74 percent of the initial flow in a 2-mile distance, or about 1.7 cfs per mile of canal.

It is concluded that artificial recharging is more economical, more beneficial, and more practical than the storage of surplus runoff in many surface reservoirs.

Lee, C. H.

1912a. An intensive study of the water resources of a part of Owens Valley, California: U. S. Geol. Survey Water-Supply Paper 294, 135 p.

As a part of the Owens Valley, Calif., investigation, measurements were made to determine percolation losses from stream channels. The percolation rate depends upon the type of material in which the channel occurs, the difference in elevation between the water surface in the channel and the ground-water surface, and the water temperature. Data showed that percolation losses were a linear function of discharge, and that percolation losses ranged from 3 to 23 percent of the total streamflow per mile.

Measurements of irrigation water losses were made on five ranches during 1909. It was determined that about 50 percent of the applied water, or 4.3 feet of water during the season, was added to the ground-water supply.

1912b. Subterranean storage of flood water by artificial methods in San Bernardino Valley, California: California Conserv. Comm. Rept. for 1912, p. 339–399.

The early development of water spreading in San Bernardino Valley, Calif., is described. Prof. E. W. Hilgard was probably the first to suggest in scientific literature the possibility of artificial recharge of ground water when he proposed in 1901 the storage of waste floodwaters of the Santa Ana River and Mill Creek by spreading them over the gravel slopes on each side of Santa Ana River. First spreading was done with Santa Ana floodwaters early in 1900. Costs and amounts of water spread are summarized.

Leggette, R. M.

1938. (and Brashears, M. L., Jr.). Ground water for air conditioning on Long Island, N. Y.: Am. Geophys. Union Trans., v. 19, pt. 1, p. 412–418.

Recharge wells are required on Long Island, N. Y., to return ground water used for industrial purposes underground. In 1937 a total of 105 recharge wells

were operating at an average rate of 0.71 cfs each. The number of such wells is steadily increasing.

Considerable care must be given to construction details of recharge wells to obtain successful operation. General practice indicates that the wells should be finished below the water table, using either large-diameter slotted pipe or spiral-wound well screens. Some wells are gravel-packed, and many are developed prior to the beginning of recharge operations. Clogging of the well screen occurs by chemical incrustation, by mechanical clogging with silt or pipe scale, or by a combination of these. Recharge wells discharging below the water table have proven more successful than those discharging above the water table. The differences may be traced to three processes which tend to cause incrustations in wells discharging above the water table. Reduction of pressure as water leaves the discharge pipe, release of dissolved gases, and contact with oxygen of the air. All these factors tend to precipitate dissolved mineral matter in the water. There should be no silt in recharge water. It is estimated that one ounce of silt in 100 gallons of water would result in more than 11 tons of silt deposition in a recharge well during a typical air-conditioning season.

Data from less than 2 years of record are not conclusive in defining the effect of recharging aquifers with warm water. Some well temperatures showed no change, while others increased up to 9° F. The rate of temperature rise can be controlled best by increasing horizontal and vertical distances between supply and recharge wells.

Le Tallec, Jean.

1954. L'infiltration "dirigée" des eaux souterraines (Directed infiltration of ground water) : Génie Civil, v. 131, no. 12, p. 233.

Drawdown of pumping wells can induce infiltration. Pumpage can thus be used to recharge the aquifers as well as supply water for distribution systems. *RCV*

Lieber, Maxim. *See also* Davids, Herbert W.

1954. (and Welsh, W. Fred.). Contamination of ground water by cadmium: Am. Water Works Assoc. Jour., v. 46, no. 6, p. 541–547.

Continuation of a study of chromium contamination of ground water on Long Island, N. Y., revealed the presence of cadmium, a heavier and perhaps more toxic metal. An analysis of the water in one recharge basin established the presence of 1.2 ppm of cadmium. Some of the ground water had a cadmium concentration of 3.2 ppm. Test wells driven on lines perpendicular to the direction of ground-water flow revealed a maximum concentration of cadmium in a zone about 33 feet above sea level, the concentrations being at a minimum at the water table and at the bottoms of the wells. The longitudinal movement of the contaminant coincided with the direction previously determined as that of ground-water movement. Many years may elapse before dilution will eliminate this contaminant from the ground water.

The discovery of this contaminant creates the urgent task of establishing a limit for cadmium in potable waters. According to the authors, it appears wise at present not to regard a drinking water as potable if it contains any cadmium in solution. *RRB*

Liefrink, F. A. *See* Krul, W. F. J. M., 1946.

Lindenbergh, P. C.

1941. Bijdrage tot oordeelkundig beheer van het duinwaterkapitaal (Contribution to the judicious management of the dune water capital): Delft Tech. Univ. Thesis, Netherlands.

This thesis contains reports of first large-scale recharge of surface water into Netherlands dunes. These experiments were undertaken to increase the water supply of Leyden.

1951. Drawing water from a dune area: Am. Water Works Assoc. Jour., v. 43, no. 9, p. 713–724.

A detailed description of the water supply for Leyden, Netherlands, is presented. As an essential feature of the system, surface water is recharged into the coastal sand dunes by means of irrigation canals. After ten years of operation the water supply is adequate and of good quality. The infiltration rate used for design of surface area of the irrigation canals is 1.3 feet per day.

Link, C. L.

1942. Installation of new gallery at Elkhart, Indiana: Public Works, v. 73, no. 12, p. 14–15, 41.

A wooden infiltration gallery built in 1884 needed frequent expensive repairs and was replaced with 18-inch porous pipe, which greatly increased the yield. Details of the installation are given.

Los Angeles County Flood Control District.

1926-1954. Annual and biennial reports on hydrologic data: Open-file report, Los Angeles.

These 19 annual and biennial reports, covering 26 years of record, summarize basic data in Los Angeles County, Calif., pertaining to stream-bed percolation, spreading grounds, ground-water levels, and special ground-water studies.

In 1953 more than 2,300 acres of spreading grounds having an average recharge capacity in excess of 1.2 feet per day were in operation. The average annual amount of water recharged in spreading grounds in the country was 52,600 acre-feet for the period 1933-53.

1952-1953 Progress reports on West Coast Basin barrier test project: Open-file report, Los Angeles.

These monthly progress reports cover operations of an experimental field project to control sea-water intrusion. Five 12-inch recharge wells were drilled in a line and spaced 1,000 feet apart. Numerous observation wells were drilled between the wells and around the line to study the effect on the ground water. The aquifer being recharged is confined by a clay cap so that recharging effectiveness is measured by pressure fluctuations. Recharging by injection has been going almost continuously since February 1953. Recharge rates range from 0.2 to 1.2 cfs per well, using fresh water containing 5–10 ppm chlorine. The recharge line has successfully built up a pressure ridge several feet above sea level. Chloride variations with time and space have been extensively observed. It was found that gravel-packed recharge wells are more effective than regular wells, and that recharge wells should be sealed above the aquifer being recharged to prevent leakage along the casing and possible subsidence.

1953. Report on the advisability of establishing water conservation zone II of the Los Angeles County Flood Control District: Open-file report, Los Angeles, 15 p.

This report recommends the establishment of a conservation zone in West Coastal Basin, Los Angeles County, Calif., to preserve and protect the ground-water resources of the basin. The area is threatened by sea-water intrusion and the zone will provide a means of financing construction of an 11-mile fresh-water ridge by a line of injection wells paralleling the coast.

Lowdermilk, W. C.

1953. Some problems of hydrology and geology in artificial recharge of underground aquifers: United Nations Educ., Ankara Symposium on Arid Zone Hydrology Proc., Sci. and Cultural Organization, Paris, p. 158–161.

Presents a general discussion of artificial recharge in arid climates. Mentions use of earth-fill dams and upstream borrow pits to obtain maximum recharge in Southern Rhodesia. Spreading works of the type developed in southern California are described. In the discussion the spreading of sediment-laden floodwater is briefly described.

Luce, A. T.

1919. The gallery collecting system of the Des Moines Water Company, Des Moines, Iowa: Am. Water Works Assoc. Jour., v. 6, no. 3, p. 475–485.

To increase infiltration into galleries bordering the Raccoon River at Des Moines, Iowa, filter basins were built in 1908 on the ground surface above the galleries. River water was recharged into these basins and thence into the galleries. Water quality was equal to that infiltrating directly from the river. Basins were 30 by 850 feet, the side slopes 1:1. Basins are used only during low-flow periods to augment water supplies. The recharge rate is about 3.1 feet per day.

Luce, J. W. *See also* Jordan, L. W., 1937a.

1933. Report of a test run on the Pacoima spreading grounds: Los Angeles County Flood Control Dist. Open-file rept., Los Angeles, 17 p.

Spreading rates were measured in ditches located in Pacoima Wash, San Fernando Valley, Calif. Rates of 6.7, 9.1, and 8.1 feet per day were obtained for separate runs of 1 to 3 hours duration.

Ludwig, R. G.

1950. Reclamation of water from sewage and industrial wastes in Los Angeles County: Sewage and Indus. Wastes, v. 22, no. 3, p. 289–295.

The report by Arnold, Hedger, and Rawn (1949) is summarized.

McGaukey, P. H. *See* Butler, R. G., 1954.

McGuiness, C. L.

1943. Ground-water resources of the Indianapolis area, Marion County, Indiana: Indianapolis, Indiana Div. Geology, 49 p.

Artificial recharge is discussed on p. 45–47. A downtown department store discharged waste air-conditioning water into an abandoned well during the summers of 1937 and 1938; however, the practice was discontinued when it was found that the temperature of the water from the main supply well had begun to rise. At two industrial plants in the area waste water was recharged in gravel pits and wells. Because of space and cost limitations, it is suggested that recharge through wells is the only practical means of artificial recharge in the downtown and congested industrial districts. Problems of clogging, cleaning, and operating recharge wells are described.

1947. Recharge and depletion of ground-water supplies: Am. Soc. Civil Engineers Trans., v. 112, p. 972–998.

Artificial recharge will be used more and more in the future as a method of conserving ground-water supplies. It is now being practiced in California; Des Moines, Iowa; Dayton, Ohio; Old Bridge, N. J.; Long Island, N. Y., Louisville, Ky., Indianapolis, Ind.; and Virginia.

1951. The water situation in the United States with special reference to ground water: U. S. Geol. Survey Circ. 114, 265 p.

The various methods of artificial recharge are described, and the leading recharge efforts in the United States are summarized (p. 67–71).

McPartland, J. W. *See* Banks, H. O., 1954.

Maffitt, D. L.

1938. Growth of a filter gallery: Water Works Eng., v. 91, no. 19, p. 1246, 1249–1250.

This article gives a historical account of the development of the Des Moines, Iowa, water-supply system on the Raccoon River. The system began with an infiltration gallery in 1871 and today includes flooding basins to augment the ground-water yield.

1943. Artificial flooding builds up ground-water yield: Water Works Eng., v. 96, no. 22, p. 1230–1232.

The water supply for Des Moines, Iowa, is obtained from horizontal infiltration galleries located below the ground-water table and parallel to the Raccoon River. To maintain the ground-water level above the galleries, flooding areas have been constructed on the ground surface. These areas are divided into basins by earth levees. The basins cover a total area of 64.5 acres and water depths of 3 to 4 feet can be obtained. Water for the basins is pumped from the river.

For efficient operation the basins are connected by a series of canals and weirs to distribute the water. Basins are alternated in use to permit aeration of the surface soil and removal of accumulated silt so that good recharge capacity can be maintained. The flooding basins are ordinarily used during periods of low stages of the river so that the turbidity of the river water is slight. Artificial recharge of ground water to maintain water supply has been in operation since 1910 and has successfully accomplished its purpose.

Magistrad, O. C. *See* Christiansen, J. E., 1945.

Martin, H.

1954. Artificial recharge of ground-water in South-West Africa: Union South Africa Geol. Survey, duplicated rept., Pretoria, 5 p.

In 1954, 30,000 cubic yards of material was excavated to form a basin to recharge a well supplying Karasburg. The well obtains its water from shales, and the basin is excavated through a layer of alluvial soil into the shales. No

quantitative results are available yet, but the water level in the well rose several feet after the basin had been filled for the first time with surface water.

The Ovamboland plain area is underlain with impervious clay layers and salt water. To improve ground-water supplies, shallow ponds have been constructed at several locations. These ponds percolate floodwaters underground where wells collect the water for use.

At Keetmanshoop plans are underway to recharge two wells with 0.3 cfs of filtered surface water. This recharging not only will conserve water for ground-water pumping but also will cut high evaporation losses of surface storage to a minimum.

Flood waters of the Swakop River near Swakopmund are pumped from a group of wells bordering the river at an upstream location. The water is carried downstream by pipe and recharged into another group of wells. The water discharges into the channel sands to dilute highly mineralized water supplying the town.

Mason, A. A. C. *See* Miles, K. R., 1952.

Mather, J. R.

1953. The disposal of industrial effluent by woods irrigation: Am. Geophys. Union Trans., v. 34, no. 2, p. 227–239.

Polluted effluent from a vegetable quick-freezing plant near Seabrook, N. J., is disposed of by spraying it from nozzles onto a wooded area. The soil is largely sand and relatively permeable. Recharge rates of 0.53 feet per day have been maintained for several months with no sign of reduced infiltration rates. The applied polluted water becomes potable after being filtered through the ground. The artificial recharge raised the water table in one season as much as 22 feet, but most of this increased storage had been discharged before the beginning of the following season.

Maxey, G. B. *See* Guyton, W. F., 1944.

Meinzer, O. E. *See also* Hall, C. W., 1911; Norton, W. H., 1912.

1917. Geology and water resources of Big Smoky, Clayton, and Alkali Spring Valleys, Nevada: U. S. Geol. Survey Water-Supply Paper 423, 167 p.

Rates of percolation from the stream bed in several streams in Big Smoky Valley, Nev., during the fall of 1914 ranged from 0.08 to 0.76 cfs per mile. Similar measurements in April 1915 ranged from 0.20 to 1.25 cfs per mile.

1937. Ground water and ground-water hydrologists in Germany: U. S. Geol. Survey open-file report, (mimeo), 11 p.

At Hamburg, Germany, part of the water supply is obtained by artificial recharge. Recharge canals and laterals extend along each side of a line of producing wells. The canals recharge surface water from tributaries of the Elbe. The method has been in operation about eight years and is regarded as very successful. No diminution in infiltration rates has been reported, the ground water remains bacteriologically pure, and the temperature nearly constant. Laterals are cleared of rushes from time to time, but muck and silt are not removed. The largest supplies of water are obtained from glacial outwash sands and gravels. Some water is obtained from Miocene sandstones at depths of 1,300 feet.

Artificial recharge was developed successfully at Frankfurt, the water being pumped from the Main; however, supplies proved to be adequate without it.

Near Gelsenkirchen in the Ruhr Valley horizontal perforated concrete pipes are laid in gravel about 150 feet from the river and deliver infiltrating water to vertical wells for pumping. The valley fill of the Ruhr in this stretch consists of gravel about 20 feet thick. Filter beds are located 150 feet from the intake pipes and about 300 feet from the river. The beds are excavated in the gravel, and consist of layers of unassorted coarse sand 1.5 feet thick. River water is led into settling basins and thence to the filters. The impervious surface "skin" which forms on the filters is removed from time to time. Less than half the total supply is derived by direct percolation from the river. By the end of summer silting of the river bed generally reduces infiltration; however, erosion associated with winter and spring floods restores the rapid rate. In years without floods as little as ten percent of the total supply occurs by river-bed infiltration. Water is normally pure, but in winter and during flood periods, it must be chlorinated.

In the Lippe River Valley a similar water-supply installation, utilizing infiltration beds and gravel-packed wells, is in operation. Here also a dam impounds surplus surface water of a tributary for recharge through the infiltration beds.

1942a. (editor). Hydrology, v. 9 *of* Physics of the Earth: New York, McGraw-Hill Book Co., Inc., 712 p.

On pages 404–405 principal methods and locations of artificial recharge are mentioned. On pages 697–698 recharge into basalt on the Hawaiian Islands is described.

1942b. (and Burdick, C. B., and Morris, S. B.). Ground water—a vital national resource: Am. Water Works Assoc. Jour., v. 34, no. 11, p. 1595–1623.

The flooding basins to supply supplemental water to infiltration galleries at Des Moines, Iowa, are mentioned. From 1 to 59 percent of the total annual pumpage is developed from the land flooding. Recharge rates are less than 1.5 feet per day, and beds are scraped at intervals of 1 to 3 years.

Water-spreading experiments at Peoria, Ill., indicate that river water could be recharged into an exposed water-bearing stratum at a rate of about 83 feet per day. The method has been demonstrated to be feasible; now a satisfactory cooperative organization is needed to carry out the project.

Spreading methods and examples in California are briefly described.

1946. General principles of artificial ground-water recharge: Econ. Geology, v. 41, no. 3, 191–201.

This paper discusses the geology and hydrology of aquifers and the principles of ground-water hydraulics as they relate to artificial recharge. Methods of increasing recharge include: indirect methods, accomplished by locating producing wells adjacent to rejected recharge or natural discharge; and direct methods, in which surface water is conveyed to points from which it percolates into a body of ground water either from surface spreading areas or by recharge through wells. Various examples of the methods are described.

Merritt, M., Jr.

1953. East Orange, New Jersey, conserves its well supply by water spreading: Water Works Eng., v. 106, no. 4, p. 286–289.

To augment the present and future water supply for East Orange, N. J., four ground-water recharge areas have been created by damming small streams and diverting surface flows into recharge ponds. The largest pond covers approximately 12 acres and the recharge rate is something over 0.51 foot per day.

In the vicinity of the recharge areas the ground-water table has been raised and the pumping capacity of wells increased. Flood gates have been installed to prevent floodwaters containing large quantities of silt from entering the ponds.

Miles, K. R.

1952. Geology and underground water resources of the Adelaide Plains area: South Australia Dept. Mines, Geol. Survey Bull. No. 27, (Adelaide), 257 p.

In an appendix by A. A. C. Mason (p. 250–257) artificial recharge of the Adelaide Plains artesian basin is discussed. Experimental recharge from existing water mains through bore holes (wells) indicates that bores operating under a pressure head of 50–100 lbs. per square inch are capable of admitting 0.75–1.1 cfs of water underground. Sites for 12 recharge bores in Adelaide have been selected with regard to location of trunk water mains and are expected to recharge up to 1,800 acre-feet annually.

Surface recharge has little application in the area because the main aquifer is confined. For 2 months in the summer of 1951 surplus surface water was recharged into 30 to 40 bores. Initially, under free flow and with heads of 50–60 feet, rates of 0.07 cfs were achieved. Infiltration rates decreased shortly, however, which caused overflowing, and the experiment was suspended.

Recharging through wells under pressure is suggested, using waters of Sturt River and Brownhill Creek near where they enter the Adelaide Plains area.

Miles, W. H.

1944. Water spreading: Soil Conserv., v. 10, no. 4, p. 73–76, 87.

Several examples are given of water spreading by New Mexico ranchers to conserve water for reducing erosion and for increasing growth of grass. In the last 4 years water-spreading systems have been established on 7,100 acres of rangeland near Tucumcari, N. Mex.

A ratio of 10 acres of drainage to 1 acre of spreading area is recommended, ratios of 5 to 1 and 25 to 1 being extreme limits. In locating a spreading area, consideration should be given to: locating a site above a gully to avoid construction of an expensive dam; placing the diversion works as near as possible to the upper end of a favorable spreading area; building the structure at a narrow and shallow point in the drainage to reduce size of the dam; looking for places where the banks of the channel below the diversion point are higher than the surrounding grassland to prevent water from returning to the gully; looking for old grassed channels into which water can be diverted to avoid the need for a dike or ditch; trying to choose a spot where no channel has been formed and where part of the water from extreme flows can be bypassed safely; selecting sites with safe and adequate spillways; putting diversion dams just below a bend in the gully channel to allow floodwaters

to jump the gully bank without changing flow direction; and choosing sites where a cut spillway will reduce the size of dam required. Various recommended criteria for design of dams, dikes, and ditches are included.

Mitchelson, A. T.

1930. Storage of water underground by spreading over absorption areas: California Div. Water Resources Bull. 32, p. 49–56.

The paper summarizes water-spreading projects in the South Coastal Basin, Calif. Water was first spread in Santiago Creek in 1896. Many small spreading operations are now practiced in the area.

Water is spread in the Arroyo Seco Canyon above Devil's Gate Dam through about 15,400 feet of ditch, 1½ to 2 feet wide, and about 2 acres in pools, covering a gross area of 35 acres. The maximum initial spreading rate was 22 feet per day, but this rate quickly reduced to an average of about 8.7 feet per day. The pools are cleaned out at the end of the season by a tractor pulling a slip scraper. An abandoned gravel pit has recently been added to the spreading grounds. As much as 4,200 acre-feet per season have been recharged at these grounds.

Experimental studies of water spreading are underway near Big Tujunga Wash, where basins 400 feet long by 40 feet wide and having side slopes of two to one have been constructed. Recharge rates, effect on the water table, direction and rate of ground-water movement, and effect of temperature and silt on percolation rates are under study.

Recharge is also being studied at an experimental plot at the mouth of San Gabriel Canyon. Water was spread for 105 days in 1930 over the 0.38-acre plot; recharge rates ranged from 3.03 to 5.33 feet per day and averaged 3.98 feet per day. The plot was in sandy soil away from the stream bed and the native vegetation was undisturbed.

1934. Underground storage by spreading water (Abs.): Am. Geophys. Union Trans., v. 15, pt. II, p. 522–523.

Geology and topography are the most important factors in selecting spreading areas. Water may be spread by a pool, by ditches, by a series of basins, and by wells or shafts. Methods of spreading in San Bernardino County, Calif., are briefly described.

Research by the Bureau of Agricultural Engineering showed that percolation rates in an undisturbed plot averaged 1.7 times more than in a furrowed plot, and 1.3 times more than a basined plot, over a 155-day period. Temperature has only a small effect on percolation rates.

1937. (and Muckel, D. C.). Spreading water for storage underground: U. S. Dept. Agriculture Tech. Bull. 578, 80 p.

This publication represents the best single source of information on water spreading for artificial recharge of ground water. The various methods of water spreading—through basin, furrow or ditch, flooding, and use of pits and shafts—are described in detail. Detailed descriptions and layouts of major water-spreading systems in southern and central California as well as natural spreading in river beds in California are presented.

Since 1930 an experimental program has been underway to obtain quantitative data on water spreading and to determine the best and most efficient method of spreading. On the San Gabriel River alluvial cone near Azusa, Calif., the results of water-spreading on plots with native vegetation, on furrowed plots, and in basins were compared. In 7 years of operation, the plot

containing native vegetation gave an average recharge rate of 5.41 feet per day, the furrowed plot gave 2.69 feet per day, and the basin plot gave 3.77 feet per day. Investigation of the effect of depth to water table on spreading rates showed no effect until the water table reached ground surface. Temperature was shown to have a minor effect on recharge rates. Near Anaheim, Calif., cleared and vegetated plots were also compared. Results were similar to those for the Azusa plots, an average recharge rate of 1.89 feet per day being obtained for one season in the cleared plot and 4.75 feet per day in the other.

Recharge rates were measured in a 4- by 6-foot timbered shaft 252 feet deep located on the Lytle Creek cone. Maximum recharge rates of 2.02 cfs were reported during one season, and 1.69 cfs in another. Measurements were made also through a nearby 16-inch well. Over two seasons of observation the maximum rate was 1.86 cfs, the minimum rate was 0.62 cfs, and the average rate was about 1.24 cfs.

Recharge rates were measured in the Lytle Creek spreading area for a short period early in 1932. An average rate of 2.50 feet per day was obtained in the spreading area and 4.28 feet per day in the stream bed.

Experimental data and observations lead to the following conclusions: greater amounts of water may be stored in subsurface reservoirs than in surface reservoirs in most regions; in many cases subsurface storage is more economical than surface storage; highest percolation rates are obtained on undisturbed land with native vegetation; consumptive-use rates are negligible in comparison with recharge rates; temperature is a small and uncontrollable factor on recharge rates; a water table in contact with the ground surface causes greatly reduced recharge rates, but a falling water table gives maximum rates; recharge rates decrease with time in spreading areas cleared of vegetation; higher rates may be maintained by frequent harrowing or raking of the ground surface; water containing silt should not be spread in still ponds; velocities should be sufficient to carry suspended matter through ditches; recharging through shafts or pits is not economical if surface spreading can be employed; ditches should return excess water back to the stream at the lower boundaries of spreading areas.

1939. Conservation of water through recharge of the underground supply: Civil Eng., v. 9, no. 3, p. 163–165.

The history, purpose, and design of recharge systems are described. The first recorded case of water spreading was that of the Denver Union Water Company in 1889, when water was spread on the alluvial cone of the South Platte River, Colo. In California, spreading by basin, furrow, and flooding methods is widely practiced, and recharging through shafts or pits is not. An experimental project of water spreading by means of a long, narrow basin on a hillside near Centerville, Utah, is under study. Tentative results appear favorable.

1949. Spreading water for recharge: Soil Conserv., v. 15, no. 3, p. 66–70.

This article contains a general discussion of purposes and methods of water spreading. Experiments show the flooding method to be the most efficient. Spreading is practiced primarily in southern California, although it first was practiced in Colorado in 1889, and is being used in Arizona, New Mexico, and Utah. The city of East Orange, N. J., spread water from a brook over 11–12 acres of absorptive land, and recharge rates amounted to about 0.5 foot per day.

Morris, S. B. *See* Meinzer, O. E., 1942.

Muckel, D. C. *See also* Mitchelson, A. T., 1937.

1936. Some factors affecting the rate of percolation on water-spreading areas: Am. Geophys. Union Trans., v. 17, pt. II, p. 471–474.

The results of water spreading in three controlled plots located in the San Gabriel River debris cone near Azusa, Calif., are described. Plots were 0.38 acre in area.

Plot no. 1 contained undisturbed native vegetation and topsoil; in plot no. 2 vegetation and roots were removed and shallow furrows 8 inches apart were formed parallel to the land slope; in plot no. 3 vegetation was removed, land was leveled, and banks were raised so that a depth of 6 to 8 inches of water could be maintained. Over several seasons of operation using relatively clear water, no. 1 averaged 5.55 feet per day, no. 2 averaged about 1.85 feet per day, and no. 3 averaged 3.84 feet per day. Consumptive use was negligible in comparison to the magnitude of the differences in percolation rates. The denuded plot (no. 3) showed the greatest variation, percolation ranging from 1 to 8 feet per day.

From observation wells located near the plots, it was found that spreading areas formed mounds on the water table, but no appreciable decrease in percolation rate occurred until the water table came in actual contact with the ground surface. The height of a mound depends upon soil type and subsurface conditions. Measurements of air and water temperatures during spreading operations showed temperature had only a small influence on the percolation.

1945. Replenishing ground-water supplies by sinking water through wells or shafts: U. S. Soil Conserv. Service (mimeo.), Pomona, Calif., 8 p.

Ground-water recharge by wells or shafts is described for five locations in southern California. Recharge rates into wells tend to decrease with time. This may be attributed to sand and fine material being forced into the aquifer, to clogging resulting from silt in the recharge water, to incrustations by chemical action in metal-cased wells, or to the effect of organic matter.

On Lytle Creek in San Bernardino County, water was recharged into a large, wood-lined shaft. A rate of 2.02 cfs was achieved in 1932, and 1.68 cfs in 1934–1935. At Perris Valley in Riverside County seven recharge wells were drilled for surface drainage. These wells, however, were unsuccessful because of silt carried into and clogging the wells. In the San Fernando Valley of Los Angeles County attempts were made to recharge through several 400–foot, 20–inch wells. The project was abandoned after a week or so because the recharge rate had decreased to a low, unsatisfactory rate. Various other short-term well-recharge projects in Los Angeles and Orange Counties are described briefly.

1948. Water spreading for ground-water replenishment: Agr. Eng., v. 29, p. 75–76, 78.

General features of water spreading, need for spreading in California, and problems arising from water spreading are discussed. *FHK*

1953. Research in water spreading: Am. Soc. of Civil Engineers Trans., v. 118, p. 209–219.

This paper summarizes recent research efforts to obtain and maintain satisfactory water-spreading rates. Laboratory studies of soil cores have

shown that percolation rates first decrease with time, then increase, and finally decrease gradually for an indefinite time. The initial decrease is believed to be caused by dispersion and swelling of soil particles; the increase accompanies elimination of entrapped air by passing water; and the gradual decrease is due primarily to biological activity in the soils. This reasoning was substantiated by tests using sterile soil and water, which gave nearly constant maximum recharge rates. These indicate that the greatest reduction in permeability can be traced to microbial growths clogging and sealing the pores.

A series of field experiments using test ponds have been conducted in Kern County, Calif. Field treatments were classified as chemical, mechanical, vegetative, operational, and additional (addition of organic matter). It is known that hard water is more conducive to rapid infiltration than soft water. Also, water containing a high percentage of sodium tends to deflocculate the colloidal soil particles and thereby hinders water movement. Applications of gypsum and calcium chloride increased percolation rates, but only temporarily. Tests with lime and copper sulfate additives were not conclusive. Mechanical tests showed that sod removal was detrimental to percolation, raking and scraping had no effect, auger holes backfilled with gravel had little or no effect, and excluding sunlight had no effect. Of several grasses tested, only Bermuda grass survived prolonged wetting and helped increase water-intake rates. The percolation rate varies with depth of water: however, depths of 0.2-0.3 foot gave better results than depths of 1-2 feet because of sunlight, temperature, or other effects. Interruptions in spreading indicated that longer drying periods were more effective than shorter ones in increasing percolation rates. In tests involving additions of several different organic materials, cotton-gin trash, consisting of boll hulls, leaves, stems, a few seeds, and a small amount of lint, resulted in substantially increased percolation rates in every trial. A 30-day moist incubation period was most effective for increasing rates. With proper drying and spading, applications are still effective after four years.

1953b. (and others). Ground water replenishment by penetration of rainfall, irrigation and water spreading in zone 3, Ventura County Flood Control District, California: U. S. Soil Conserv. Service, Los Angeles, 63 p.

A portion of this report (p. 40–63) covers an investigation to locate grounds where water-spreading is feasible in part of Ventura County, Calif. Selection of areas was based upon the criteria that the surface soil must be receptive to water, that there should be little or no subsoil development, which restricts the downward movement of water, and that the topography should be such that relatively large areas can be submerged inexpensively for spreading purposes. Other factors of importance but not covered in this investigation are that no continuous impervious or relatively impervious strata should occur between the soil mantle and the main aquifer, that the aquifer should have sufficient capacity to receive any water spread and to provide for required carry-over storage, and that spreading basins should be located so that recharged water will eventually reach the intended aquifers.

The study consisted of examination of soil survey maps and field measurements with infiltrometers. Based upon these data, recommended spreading areas were delimited and estimates of recharge rates were prepared.

Mulford, L. *See* Bush, A. F., 1954.

Nebolsine, R.

1943. New trends in ground-water development: New England Water Works Assoc. Jour., v. 57, 186–200.

The Ranney water collector for induced infiltration, principles, construction, engineering features, and typical installations are described, and data on performance and water quality are given.

Nelson, T. C.

1949. New Jersey ground-water supplies: Am. Water Works Assoc. Jour., v. 41, no. 6, p. 507–510.

Artificial recharging of aquifers at Newark and Duhernal, N. J., is mentioned. Suggests that a system of surface reservoirs on New Jersey streams would provide flood control and also maintain ground-water levels by recharge.

Nelson, W. B. *See* Thomas, H. E., 1948.

Nerreter, B.

1932. Wasserversorgung im mittleren Ruhrkohlenbezirk mit besonderer Berücksichtigung der Stadt Essen (Water supply in the central Ruhr coal region with special reference to the city of Essen): Gas- u. Wasserfach, v. 75, no. 33, p. 653–660.

The water supply for Essen, Germany, and surrounding area is obtained from the Ruhr River by means of a complex system of infiltration basins, infiltration galleries, wells, and pumping plants.

This article describes and illustrates how these systems function. Basically, river water is recharged into the adjacent infiltration basins, from which the infiltrated water is collected by galleries and wells for use. Maximum recharge rates exceed eight feet per day. Variations of recharge rates, water temperatures, and seasonal changes in water quality are described.

Norris, S. E.

1948. The water resources of Montgomery County, Ohio: Columbus Ohio Water Resources Board Bull. 12, p. 6, 52–56.

This report discusses in detail artificial recharge by channels in Rohrer's Island well field of Dayton municipal water supply and Bimm's pond along the lower course of Mad River. *FHK*

North Kern Water Storage District.

1947. Folio of spreading test graphs, 1936–1946: San Francisco, Calif., 69 p.

This publication consists of a series of graphs of water spreading rates in several ponds in Kern County, Calif., during 1936-1946. The graphs show the variations of recharge rates under a variety of soil and surface-treatment conditions.

1948. Folio of spreading test graphs, 1947: San Francisco, Calif., 29 p.

This publication consists of a series of graphs of water spreading rates in Minter and Wasco ponds in Kern County, Calif., during 1947. The graphs show the variations of recharge rates under a variety of soil and surface-treatment conditions.

Norton, W. H.

1912. (and Hendrixson, W. W., Simpson, H. E., Meinzer, O. E. and others). Underground water resources of Iowa: U. S. Geol. Survey Water-Supply Paper 293, p. 661, 667.

Use of drainage wells is suggested to drain swampy or marshy agricultural lands where water levels in bedrock stand at some depth below the surface. *FHK*

Orlob, G. T. *See* Butler, R. G., 1954.

Pearse, C. K. *See* Stokes, C. M., 1954.

Peoria Association of Commerce.

1951. Dedication ceremonies—water infiltration recharge pit: Water Conserv. Comm., 5 p.

A new recharge pit constructed to determine possibilities of artificial recharge by infiltration at Peoria, Ill., is described. The pit has bottom dimensions of 40 by 62.5 feet and is so situated that it will obtain a gravity flow of water from the Illinois River. River water will be chlorinated before recharging. The pit area is covered by a sand filter. It is estimated that the pit will allow infiltration of about 3.1 cfs. As relatively cool and clear river water is available only about half the year, an average recharge rate of 1.55 cfs is anticipated.

1952. Report on Peoria infiltration pit: Water Conserv. Comm., 5 p.

Results of the first operating season of the recharge program using the infiltration pit at Peoria, Ill., are reported. The pit was operated for 146 days with an average inflow of 2.75 cfs from the Illinois River. Water was run into the pit only when the river temperature was 60°F or less and the river turbidity less than 100 ppm. The water was chlorinated an average of 3.62 ppm, screened, and filtered through a 6-inch sand layer in the pit. Recharging raised the ground-water level within half a mile of the pit an average of 4.35 feet at the end of the infiltration season. It was necessary to clean the pit 9 times during the 7 months of operation. Samples of water from observation wells showed that recharged water satisfactorily met drinking water standards. Ground-water temperatures were lowered substantially by the recharge operations. Silt accumulates in a layer on top of the sand and penetrates the sand less than 2 inches; slight scraping can restore the pit to its original capacity. The pit should never be emptied during freezing weather, as a frozen dry pit is impervious and cannot be defrosted with 32°F river water.

Problems under study include removal of the silt, cleaning of the fine screen, removal of the debris at the control tower, and effects of special weather conditions.

1953. Report on Peoria infiltration pit, 1952–1953: Water Conserv. Comm., 5. p.

Results of the second operating season of the recharge program using the infiltration pit at Peoria, Ill., are reported. The pit was operated for 208.5 days with an average inflow of 1.60 cfs. No cleaning was done during the operating period, and the recharge rate therefore dropped from 3.1 to 0.99 cfs at the end of the period. The average chlorination rate was 8.8 ppm. The surrounding water table rose when the recharge rate exceeded 2.3 cfs, but started to drop when the rate was reduced to 1.5 cfs. A method was developed

to keep the fine screen clean. Water of turbidity exceeding 100 ppm should not be used as it was found that greater concentrations caused marked reductions in recharge rates. Tests were made which indicated that it is possible to remove the top silt from the sand with the help of a swimming-pool suction cleaner. Very little silting was found in the lower portion of the 6-inch sand layer even after 7 months of continuous operation. Recommendations are made for design changes of a new pit. Hydraulic-model studies of flow conditions around and under the pit are underway.

1954. Report on Peoria infiltration pit, season 1953–1954: Water Conserv. Comm., 8 p.

Results of the third operating season of the infiltration pit at Peoria, Ill., are reported. The pit was operated for 199.25 days with an average inflow of 1.63 cfs. No intermediate cleaning or changing of the sand was done during the operating season with the exception of some suction cleaning toward the end of the season. The initial inflow rate was 3.02 cfs, which decreased to 1.7 cfs after 10 days, and decreased more slowly to 1.2 cfs by the end of the period. (Average chlorination was 8.8 ppm, the chlorine costing 8 cents per pound.) A new suction cleaner (swimming pool type) was installed, which effectively reduced the silt layer and increased the recharge rate. The average river water turbidity of 90 ppm, introduced 77 tons of silt into the pit. Water samples from a well 100 feet distant showed 20 to 50 organisms per milliliter but no coli organisms. Highest counts appeared when the pit operation started, indicating a washout of soil organisms by the first recharge water. Some algae appearing in the river water tended to clog the pit, but use of copper citrate killed them. Ground-water levels around the well rose 1 to 2 feet when the pit was put into operation, but then lowered slowly to pre-operating levels after 5 months.

Model studies show that the inflow of a pit does not increase proportionately to the size of the pit, that the main inflow occurs through the sides of a pit and not through the bottom, that facility of getting water away from the pit underground is more important than the permeability of the soil-water boundary, and that no air binding occurs in the pit bottom.

Phelps, E. B. *See* Winslow, C. E. A., 1906.

Piper, A. M.

1939. (and Gale, S. H., Thomas, H. E., and Robinson, T. W.). Geology and ground-water hydrology of the Mokelumne area, California: U. S. Geol. Survey Water-Supply Paper 780, 230 p.

This paper gives results of studies to determine the extent to which the ground-water supply depends upon water from Mokelumne River, Calif., and the extent to which the supply may be influenced by regulation of the stream. Concludes that Pardee Dam affords a means of regulating the discharge so as to effect a maximum ground-water replenishment. *FHK*

Poland, J. F.

1950. Ground water in California: Am. Inst. Min. Met. Engineers Trans., v. 187, p. 279–284.

The importance and need for study of artificial recharge to conserve water in the San Joaquin Valley and to control sea-water intrusion in Los Angeles County, Calif., is described.

Porter, N. E.

1941. Concerning conservation of underground water with suggestions for control: Am. Soc. Heating and Ventilating Engineers Trans., v. 47, p. 309–322.

In Sacramento and Fresno, Calif., the amount of cooling water returned to the sewer systems is limited by city ordinance. Disposal wells have been drilled to dispose of excess water. In Sacramento, water is usually supplied from the 120-140-foot strata and returned to the 65-80-foot strata. In Fresno, where many disposal wells have been in operation for some time, a serious rise in ground-water temperature occurs over the summer period.

Potrykus, F.

1952. Die Wasserversorgung der Stadt Essen (The water supply of the City of Essen): Gas- u. Wasserfach, v. 93, no. 10, p. 268–276.

The water supply for Essen, Germany, and infiltration basins and collecting galleries for using recharged Ruhr River water are described.

Powell, S. T.

1948. Some aspects of the requirements for the quality of water for industrial use: Am. Water Works Assoc. Jour., v. 40, no. 1, p. 8–23.

Recharging aquifers with cold, treated water during the winter is a relief measure for industrial areas faced with an overdraft.

Rafter, G. W.

1897. Sewage irrigation: U. S. Geol. Survey Water-Supply Paper 3, 100 p.

In discussing quantities of sewage applied to land, it is pointed out that the recharge rate depends largely upon the soil type. Recharge rates in Europe range from 0.007 to 0.09 foot per day.

Ranney Method Water Supplies, Inc.

1953. The Ranney system of water production for industrial and municipal use: Columbus, Ohio, 20 p.

The Ranney collector well, used for collecting ground water and for collecting induced recharge by infiltration from surface-water sources, is described and illustrated.

Information on installations in the United States is tabulated. Of 79 river infiltration units, the average water-producing capacity per unit is about 11 cfs. Similarly, for 19 units operating as ground-water collectors only, the figure is about 6 cfs.

Rawn, A. M. *See also* Arnold, C. E., 1949.

1949. Water from wastes: concepts and costs: Eng. News-Rec., v. 143, no. 9, p. 172–174.

The author states that effluent from sewage reclamation plants should be spread on infiltration beds if used to recharge ground water. On the basis of long-period operation of sand beds for spreading of floodwaters in Los Angeles County, Calif., effluent spreading would cost about $2 per million gallons. Effluent recharge through wells will not be practical because suspended organic matter will clog sand interstices. Experiments in spreading sewage-treatment-plant effluent at the rate of 1.0 foot per day for 14 days showed no pollution or anaerobic conditions 4 to 7 feet below ground surface. As a result of these tests, a natural sand bed may be expected to operate successfully at an equivalent rate on a 2-week cycle. The cycle would include percolation for about a week, drying out, aerating, and complete reconditioning of the surface of the bed.

1950. Blending of sewage effluent with natural waters permits reuse: Civil Eng., v. 20, p. 324–325, 373.

In recharging ground water with sewage effluents, well-oxidized, secondary effluent is recommended over primary sewage-plant effluents. The objections to the latter do not include contamination, but do include the likelihood of odor nuisance, mosquitoes, and reduced rate of percolation requiring more and larger bed areas or more frequent cleaning.

1952. Reclamation of water from sewage and industrial wastes, *in* The physical basis of water supply and its principal uses: U. S. Cong., House Comm. on Interior and Insular Affairs, p. 89–93.

Water-reclamation processes for sewage treatment plant effluents and spreading grounds to recharge underground reservoirs are described.

1953. (and Bowerman, F. R., and Stone, R.). Integrating reclamation and disposal of waste water: Am. Water Works Assoc. Jour., v. 45, no. 5, p. 483–490.

Artificial recharge is an important part of an integrated system of waste water disposal and reclamation.

Reagan, J. W.

1924. Upon the control of flood waters in this District by correction of rivers, diversion and care of washes, building of dikes and dams, protecting public highways, private property and Los Angeles and Long Beach harbors: Los Angeles County Flood Control Dist., Los Angeles, 20 p.

Plans for flood-control works in Los Angeles County, Calif., and provisions for spreading grounds for recharging floodwaters are described.

Reber, A. W. *See* Jordan, L. W., 1937.

Remson, Irwin.

1954. Hydrologic studies at Seabrook, New Jersey: Columbia Univ., New York, Doctoral dissert.

About one billion gallons per year of waste water derived from food-processing operations is disposed of by means of "woods irrigation' at Seabrook Farms, N. J. The successful functioning of the system depends on local topography, geology, hydrology, soils, climatic balance, and flora. The effect of these factors in artificial recharge is studied and evaluated. *RCV*

Rhoades, J. F.

1942. Ranney water collector systems: Paper Trade Jour., v. 114, no. 8, p. 123–124, 126, 128.

Design, operation, and costs of Ranney water collectors for obtaining ground water by induced infiltration are described.

Richert, J. G.

1900. On artificial underground water: Stockholm, C. E. Fritze's Royal Book-Store, 33 p.

This paper presents one of the earliest and most complete statements of the advantages of artificial recharge to augment water supplies. Methods for inducing infiltration, by use of infiltration galleries or wells adjacent to surface-water bodies, and infiltration basins are described in detail. Examples of different systems and possibilities for others in several European cities are described.

Successful induced infiltration systems at Goteborg and Schweinfurt on-the-Main are mentioned as well as unsuccessful ones at Toulouse and Vienna. Infiltration ditches for recharge have been used at Wiesbaden, Remscheid, and Chemnitz. Induced infiltration systems are to be built at Lulea, Jonkoping and Uddevalla, and an infiltration system at Goteborg, all in Sweden. Suggests that infiltration basins would be advantageous for the Swedish cities of Stockholm, Helsingfors, and St. Petersburg, as well as for the European cities of Amsterdam, Brussels, Toulouse, Paris, Berlin, and Vienna. The local situation at each city is described briefly and the way in which artificial recharge methods could be applied.

1902. Künstliche Infiltrationsbassins (Artificial infiltration basins): Gasbeleuchtung u. Wasserversorgung Jour., v. 45, no. 51, p. 963–964.

Various methods of increasing water supplies by recharging surface water into nearby infiltration basins and collecting the water from wells or galleries are outlined. As an example, the installation at Gothenburg, Sweden, is mentioned. Recharge rates there equal about 4.3 feet per day, and quality of water obtained is excellent.

A proposed recharge system for London, England, is briefly sketched. It would consist of a line of ten recharge basins, 325 feet by 650 feet, from which the recharged water would travel 3,300 feet through sand to a parallel line of pumping wells in 250 days. A recharge rate of 3.3 feet per day was assumed.

1904. The progressive sinking of the ground-water level and artificial ground-water supplies: Eng. News, v. 52, p. 474–475.

Lowered ground-water levels can be raised by artificial infiltration. Open infiltration ponds with controlled flows in porous ground are recommended for this purpose. The applied water is filtered, biological contamination is removed, temperatures are equalized, and the water assumes the character of the natural ground water. These cleanable infiltration basins are used by Swedish towns to augment their water supplies.

Richter, R. C. *See* Banks, H. O., 1953 and 1954.

Riedel, C. M.

1934. River water used at Dresden to increase ground supply: Eng. News-Rec., v. 112, no. 18, p. 569–570.

The Hosterwitz plant of the Dresden, Germany, water works obtains its water supply by artificial ground-water recharge. Water from the Elbe River is pumped into concrete settling basins. In 4 hours, 30 to 60 percent of the suspended matter settles out. From here the water is pumped to closed rapid-sand filters for removal of the remaining suspended matter. The water is then recharged through open-air infiltration basins after sprinkling for aeration. The bottoms of the basins contain 8 inches of sand. After a certain length of service the manganese algae that grow on the sand bed are removed by scraping off about 1 to 2 inches of the sand surface, cleaning the sand at a nearby washing plant, and then replacing it. Wells located about 200 feet from the infiltration basins pump the recharged water for city consumption.

Roberts, C. M. *See* Halberg, H. N., 1949.

Robinson, T. W. *See* Piper, A. M., 1939; Stearns, H. T., 1930.

Roe, H. B.

1950. Moisture requirements in agriculture: New York, McGraw-Hill Book Co., Inc., 413 p.

Part of this book (p. 162–164) discusses factors influencing deep percolation and canal losses in use of water for irrigation.

Roemer, G. B.

1948. The influence of seasonal factors on the properties of shore-filtered Rhine water: Gesundheits-Ingenieur, v. 69, p. 44–51.

The average bacterial count of the water of the Rhine is 6000–8,000 per cc. The results of regular tests made in several water works of Dusseldorf in 1939–42 showed that the average count was far below 100 in the soil-filtered water, although at times it suddenly rose to over 1,000. The filtering action of the soil is lost during the winter because of the death of organisms which destroy bacteria, the reduced activity of the sludge layer in the bottom of the river, and the frequent and sharp variations in the height of the river. The chemical data are affected by the admixture of true ground water from the land. The chloride content has risen from earlier values of 30 mg/1 to 70 mg/1 as a result of industrial sewage emptied into the river. The nitrate content of the well water parallels that of the Rhine water but is higher because of oxidation in the soil. The reverse is true for the nitrite and NH_3 contents. *MGM*

Rogers, N. *See* Steinbruegge, G. W., 1954.

Roper, R. M.

1939. Ground-water replenishment by surface water diffusion: Am. Water Works Assoc. Jour., v. 31, no. 2, p. 165–179.

To increase ground-water supplies the city of East Orange, N. J., has built several water-spreading ponds. Diversion dams on nearby creeks direct water to the spreading areas. The largest area covers 11 or 12 acres and a recharge rate of about 0.5 foot per day has been maintained for long periods. To prevent silt from entering the ponds, automatic floodgates which stop diversions when the stage reaches a predetermined level have been installed. The spreading has increased yields and reduced drawdown in adjacent pumping wells.

Rorabaugh, M. I.

1946. Ground-water resources of the southwestern part of the Louisville area, Kentucky: U. S. Geol. Survey open-file rep., 39 p.

This report presents detailed information for use in the development of ground-water supplies southwest of Louisville and discusses in some detail river infiltration and induced recharge. *FHK*

1949. Progress report on the ground-water resources of the Louisville area, Kentucky, 1945–49: City of Louisville and Jefferson County, Kentucky (dupl. rept.), 64 p.

Recharge of city water into gravel and sand aquifers of glacial age in the Louisville area, Ky., was practiced from 1944 to 1948. Since 1947 water used for air-conditioning has been returned to the ground through recharge wells. Such wells have been successful where designed specifically for recharge operations. During 1948 an average of 2.0 cfs of used water was returned to the glacial outwash deposits from which it was pumped. Recharge through pits is being considered. Water spreading is not feasible because the outwash deposits are covered by clay and silt of low permeability. The use of artificial recharge will probably increase in the Louisville area in the future.

1951. Stream-bed percolation in development of water supplies: Union Géod. Géophys., Internat. Assoc. Internat. Hydrologie Sci., Assemblée Gén. Brussels 1951, v. 2, p. 165–174.

Since World War II large supplies of water have been developed in the Ohio Valley by placing tubular wells or horizontal-type collector wells near a surface stream where permeable glacial-outwash deposits underlie the valley floor. Stream water is induced to percolate downward through the stream bed by pumping from the wells. Design of a system depending on stream-bed percolation requires a knowledge of hydrologic and geologic factors determined from test drilling and pumping tests.

Factors to be considered are permeability, thickness, storage capacity, and storage coefficient of the aquifer, unwatering of the aquifer, available head, head loss associated with the installation, interference from other installations, and viscosity changes due to temperature.

The following performance data were determined for the period 1945–1950 for a horizontal-type collector located along the Ohio River: an increase in yield during floods; a decrease in yield after floods because of removal of water from storage and reduction of the saturated thickness of the material; and a substantial decrease in yield during the winter when river-water temperature drops to 32° F and viscosity increases.

Silting of the river bed has not been sufficient to cause any reduction of yield. The temperature of the water pumped ranges from 47° to 64°F and lags about 10 weeks behind the seasonal temperature cycle of 32° to 85°F of the river water. Temperature curves of the water from individual horizontal screens in the unit show a greater range in temperature and less time lag for those nearer the river than for those landward from the unit.

The mineral content of water derived from stream-bed percolation is intermediate between that of the river and that of the acquifer. The process usually produces a water free of bacterial contamination, turbidity, and chemical wastes.

1956. Ground-water resources of the northeastern part of the Louisville area, Kentucky with reference to induced infiltration: U. S. Geol. Survey Water-Supply Paper 1360–B, p. 101–169.

Data collected in investigations of the glacial valley-fill deposits along the Ohio River in the northeastern part of Louisville, Ky., are analyzed. The principal aquifer in this area consists of about 80 feet of glacial-outwash sands and gravels partially filling an older, deeper valley cut into limestones, shales and dolomites of Ordovician, Silurian, and Devonian age. The trans-

missibility was determined by a pumping test as 121,000 gallons per day per foot in the test area; the distance to the line source, 400 feet; and the coefficient of storage 0.0003.

Existence of a connection between the river and aquifer was shown by means of chemical analysis, sections showing temperature distribution in the aquifer during the pumping test, shapes of water-level profiles in the test area, and shapes of time-drawdown curves for a number of observation wells. Hydologic constants of the aquifer were determined by both graphical and mathematical methods. It was estimated that under adverse temperature and river-stage conditions, 433 cfs for the 6.4-mile stretch of river investigated could be infiltrated. *FHK*

Ross, R. M.

1946. Spreading water through wells as a possible means of conserving pre-irrigation season water from Millerton Lake: U. S. Bur. Reclamation, 28 p.

Various recharge operations through wells in California are summarized. Water was recharged into existing wells of the Lindsay-Strathmore Irrigation District during the spring of 1932. Some 2,000 acre-feet of water were recharged into 82 wells for an average of about 45 days per well. Well capacities varied from 0.07 to 1.0 cfs. The water table rose an average of 33 feet over an area of 12,000 acres. Only clean water was recharged, it being settled and screened twice before recharging. Costs averaged about $5.00 per acre-foot, most of this being for electric power to lift the water. No wells clogged during the recharging, and it was found that water may be recharged into a well at substantially the same rate that it may be pumped. Since 1933 the District has recharged water by spreading on the Kaweah Delta, this method being cheaper than using recharge wells.

Water has been recharged through a 105-foot well and a shaft 70 feet deep and 6 x 8 feet across near Orange Cove, Calif., for more than 10 years. The well takes water at a rate of 0.67 to 0.90 cfs. There has been a gradual but relatively small reduction in the recharge rate. Recharging has raised the surrounding water table and provided a substantial portion of required irrigation water.

Cooling water from a refrigeration plant in Fresno, Calif., is recharged into a 12-inch well 225 feet deep. The well is perforated at a lower level than that of a nearby pumping well so that warm water will not be pumped. The well is recharged daily for 21 to 22 hours at a rate of 0.95 cfs. Its capacity is greater than this, but has never been reached. The success of the well is attributed to the clearness of the recharge water. Another recharge well also used to return cooling water to the ground in Fresno took water at a rate of 0.78 cfs for the 15 months that it was in operation. At an ice plant in Fresno, water is recharged through two wells. These wells were used 24 hours a day during the ice-making season for 10 years. The well now has a capacity of 0.67 cfs and is recharged 9 hours per day. The second well has become partially sealed; the reason is unknown.

It is concluded that water can be recharged satisfactorily through wells if the water is clean, if its dissolved-salt content—particularly sodium—is reasonably low, if the wells are kept full during the recharge period, and if the costs are not too high. Costs of well recharge depend upon such factors as character of existing wells, existence of pipe or other distribution systems, distance of wells from the water source, and subsurface conditions. Experimental studies of the method are strongly recommended.

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Safay, F. A.

1937. Drainage well sanitation: Florida Health Notes, v. 29, p. 109–110.

The state law of Florida prohibits use of drainage wells without permit. The cooperation of drillers and well users to avoid possible contamination and typhoid fever epidemics is requested.

Sampson, G. A.

1934. Engineering problems connected with recent improvements to the Newton, Massachusetts, water supply works: New England Water Works Assoc. Jour., v. 48, no. 1, p. 88–101.

As part of an expanded water supply system for Newton, Mass., flooding basins were established in gravel beds adjoining the Charles River. Basins were prepared by stripping the area of trees and surface soil to expose gravel. In one basin of 0.64 acre, a recharge rate of 4.3 feet per day was established, and 62 percent of the water pumped from the river for recharge appeared in nearby wells as increased pumpage. It was found that a distance of 150 feet between the recharge area and pumping wells was more than ample for purification of the water in the coarse gravel.

Over 50 percent of the total water supply is derived by infiltration from flooded gravel areas.

Sanford, J. H.

1938. Diffusing pits for recharging water into underground formations: Am. Water Works Assoc. Jour., v. 30, no. 11, p. 1755–1766.

This article describes the practical problems encountered in enforcing recharge underground of water from new wells used for cooling and air-conditioning purposes on Long Island, N. Y. Recharge wells of 4- and 8-inch diameters were first installed because they were cheap, but they tended to clog easily. In 1938 there were 106 recorded recharge wells. Recharge capacities of wells for air-conditioning range from 0.17 to 1.3 cfs, while those for manufacturing plants range from 0.67 to 2.2 cfs. No standard recharge-well construction has evolved, but in most installations a pit of 30-inch diameter or more contains a center pipe extending to the bottom of the well. The pipe should be no less than 8 and preferably 12 inches in diameter, and contain ample well screen of the best quality. Outside the screen there must be a wall of graded filter gravel having a minimum thickness of 2 inches. The gravel must surround the center pipe to the top and connect with the pit. Pumping and recharge wells should be at least 100 feet apart and, if possible, should be finished in different aquifers to avoid pumping warm, recharged water.

Tests have indicated that recharge rates of 4.5 to 6.7 cfs can be achieved in wells located in coarse gravels by building up back pressure from a pump. These wells could not be pumped at rates above 0.9 to 1.1 cfs.

Recharge wells can be cleaned in the same manner as pumping wells. Well-cleaning reagents, in order of importance, are dry ice, hydrochloric acid, and sulphuric acid.

Sayre, A. N.

1948. (and Stringfield, V. T.). Artificial recharge of ground-water reservoirs: Am. Water Works Assoc. Jour., v. 40, no. 11, p. 1152–1158.

A general discussion and review of ground-water recharge and numerous brief examples are given.

Scalapino, R. A.

1949. Ground-water resources of the El Paso area, Texas, progress report 6: Tex. Board Water Engineers, 22 p.

Results of artificial-recharge tests indicate that it may be practicable to inject surface water into the ground-water reservoir for later use. Such recharge would also be advantageous in maintaining the water table and artesian pressure at higher levels, which in turn would halt or retard the rate of ingress of salt water into the fresh-water sands. Data show that recharge at the rate of 9 cfs for 90 days would raise the artesian pressure about 10 to 35 ft. *RCV*

Sceva, Jack E.

1950. Preliminary report on the ground-water resources of southwestern Skagit County, Washington: U. S. Geol. Survey open-file report, 40 p.

Possibilities and limitations of inducing infiltration from the Skagit River by heavy pumping of wells are discussed. *RCV*

Scheelhaase, F.

1911. Beitrag zur Frage Erzeugung künstlichen Grundwassers aus Flusswasser (Contribution to the problem of producing artificial ground water from river water): Gasbeleuchtung u. Wasserversorgung Jour., v. 54, no. 27, p. 665–675.

This article discusses basic principles of operations in which surface waters are recharged into aquifers and pumped from wells for water supply. An example of the use of the method is the installation at Frankfort, Germany, in which Main River water is used. Details of the installation, its success in three years of operation, and water quality and temperature of the artificial ground water are presented.

1923. Wasserversorgung mit Flusswasser oder mit künstlich-erzeugtem Grundwasser (Water supply with river water or with artificially produced ground water): Gesundheits-Ingenieur, v. 46, no. 48, p. 461–464.

After a general discussion of artificial recharge for water supply, the author describes the plant at Frankfort, Germany. This installation pumps Main River water through filters and into trenches bordering the river where it infiltrates underground. Wells paralleling and below the trenches pump the water for use. Water-quality aspects of the system are examined.

1924. (and Fair, G. M.). Producing artificial ground-water at Frankfort, Germany: Eng. News-Rec., v. 93, no. 5, p. 174–176.

In 1908 an experimental artificial recharge plant was constructed at Frankfort, Germany, in an effort to increase the available ground-water supply. Main River water was used, but, because of its high turbidity and organic load, preliminary treatment was necessary. The water was passed through a mechanical filter and a slow sand filter. The water was then recharged in two 80-foot branches of tile pipe situated 10 feet below ground surface and laid with open joints. The pipes are used alternately, the water passing through the open joints into the ground. The plant capacity is 0.2 cfs. The recharged water percolates through 43 feet of sandy materials and reaches the ground-water table in about 14 days. The recharged water was found to be of satisfactory quality, so much so that at a distance of 500 feet from the point of recharge it could not be distinguished from the best ground water. No operational difficulties have developed during 12 years of operation.

In 1921 a larger recharge plant was built with a capacity of 0.8–1.5 cfs and using open ditches instead of the subsurface tile pipe. Good results have been obtained.

Schiff, L. *See also* Bliss, E. S., 1950.

1952. Some developments in water spreading: U. S. Soil Conserv. Service, Bakersfield, Calif., 31 p.

This report describes field research on water spreading in the San Joaquin Valley, Calif.

Treatment of soil with cotton gin trash and the growing of Bermuda grass, have increased infiltration rates in small basins (0.005 acre). The operational procedures, such as length of wetting and drying periods, continuous or intermittent flooding, and soil manipulation, are as important as the treatment in obtaining beneficial results. Studies of soil samples after treatments have shown improvement in the surface soil as a medium for the more rapid transmission of water. Using similar treatments and operational procedures, it should be possible to achieve similar improvement on larger areas. However, it would not be economically sound to treat surface soils to increase infiltration rates beyond the ability of soil horizons below to transmit water, unless treatments can be developed that affect such horizons. Surface compaction by heavy equipment, particularly when they have made many passes over wet soil during preparation of a spreading area may reduce infiltration rates greatly. If appreciable compaction takes place, it must be offset by other tillage operations or perhaps by wetting and drying over a period of time in order to obtain the beneficial effect of the surface treatment. Results of tests indicate that, for certain soils and topography, sufficient increase in infiltration rates may be obtained by increasing the surface head.

New treatments seem to offer some promise in exploratory studies. For example, CRD–186 (Krilium), increased infiltration rates immediately after application. Its action is similar to that of decomposed organic matter but, unlike organic matter, it is reported to resist microbial decomposition. Local soils vary from medium to coarse in texture. They display a low initial aggregation and respond to Krilium much more rapidly than fine-textured soils which already possess a high percentage of water-stable aggregates. Pumice, although not increasing the maximum rate, seemed to sustain infiltration rates at a higher level than normal for a prolonged period of submergence.

Small units may be used to estimate the infiltration rates of a large area if proper corrections can be made for laterial flow. Where pressure exists at the bottom end of the borders forming the unit, a "balancing buffer" (pool of water surrounding the small unit and of equal depth or surface head) may be helpful.

1953. The effect of surface head on infiltration rates based on the performance of ring infiltrometers and ponds: Am. Geophys. Union Trans., v. 34, no. 2, p. 257–266.

Studies with infiltrometers and small ponds indicate that the normal low infiltration rates of certain soils may be increased by providing sufficient depth of water on the soil surface.

1954. Water spreading for storage underground: Agr. Eng., v. 35, no. 11, p. 794–800.

Results of various soil treatments and operational procedures to increase recharge rates are reported from field tests in Kern County, Calif. Treatments

investigated include: vegetative—cotton-gin trash treatment and growth of Bermuda grass; chemical—Krilium, Orzan, Flotal; mechanical—injection shafts and injection ditches; and operational—depth and location of treatment, size and shape of spreading areas, arrangement of areas, length of incubation and drying periods, cultural operations, and surface head.

Gases, produced by micro-organisms in the soil as they break down organic matter, have a greater opportunity to escape under alternate-area water spreading. When large areas are flooded, particularly for a long period of time, some of this gas is trapped and retards the downward movement of water. Low infiltration rates for a long period of time are conducive to the development of anaerobic conditions and to the production of gases that are not readily soluble.

Injection shafts and ditches dug through less pervious subsurface soil horizons have increased infiltration rates.

Schmidt, H.

1951. Flussgrundwasser (River ground water): Gesundheits-Ingenieur, v. 72, no. 10, p. 166–168.

Ground-water temperatures and hydraulics for pumping wells located near streams in order to induce infiltration are described.

Schneider, H.

1941. Versickerung und künstliche Grundwasseranreicherung (Percolation and artificial ground-water recharge): Gesundheits-Ingenieur, v. 64, no. 13, p. 191–196; no. 14, p. 205–210.

This paper presents a comprehensive analysis of the hydraulics of recharge wells. Beginning with the equation expressing the drawdown curve for a pumping well in an unconfined aquifer, the equation for the reverse curve around a recharge well is derived. Relations among the variables—recharge rate, aquifer thickness, recharge mound height, permeability, and well radius —are examined in detail. Similar relations are derived for a recharge well penetrating a confined aquifer.

The hydraulics of recharge basins is examined, and relations of recharge rate, temperature, depth to water table, depth of water in the recharge basin, permeability, and width of recharge basin are established. The concluding section of the paper discusses installations of waterworks based upon artificial recharge. Locations of recharge wells and pumping wells should roughly parallel the natural ground-water contours, recharge wells being upstream from pumping wells.

1952. (and Truelsen, C., and Thiele, H.). Die Wassererschliessung (Water development): Essen, Germany, Vulkan-Verlag, 421 p.

Idealized physical relationships between artificial ground-water recharge and discharge areas are described and illustrated on pages 150–155.

Schubel, F. W.

1936. Die hygienische Untersuchung und Beurteilung der künstlichen Grundwasseranreicherung (The hygienic investigation and evaluation of artificial ground-water recharge): Hygiene u. Bakteriologie Archiv., v. 116, no. 6, p. 321–364.

A survey is presented of the present state of artificial recharge of ground water for domestic supplies with particular emphasis on the hygienic aspects.

Hygienic provisions of the recharge installation at Bamberg, Germany, were investigated and are described in detail.

Water for recharging at Bamberg comes from surface streams which drain peat areas and fields containing manure fertilizers. This water after recharging is biologically pure. Fluorescein was added as a tracer to the recharged water to determine its movement underground. It was found that the water remained underground for a minimum of 66 days and traveled at rates of 1.5 to 18 feet per day on slopes as high as 1.33 percent toward the collecting location. Phage probably will not be filtered out by the soil, but instead will travel at approximately the same rate as the tracer. The Bamberg recharge operated at a maximum rate of 17 feet per day for 25 days in 1935 without harmful effects. Similar operating conditions can be anticipated for the future if basin drying periods and travel distances underground are not reduced. Fluorescein has several drawbacks as a ground-water tracer.

A table lists 20 German artificial-recharge installations and includes data on date of installation, method of recharge, recharge surface area, daily quantity recharged, recharge rate (varying from 0.75 to 8.2 feet per day), duration of recharged water underground before use, pretreatment, surface-water source, and temperatures of water before and after recharging.

A comprehensive bibliography of 244 references, mostly German, concludes the paper. The references are grouped by subject and include 27 books, 108 papers on artificial recharge of ground water, 29 on hydrology and geology, 40 on hygiene and bacteria, and 39 on the use of tracers for ground-water investigations.

Segel, A.

1950. Sewage reclamation at Fresno, California: Sewage and Indust. Wastes, v. 22, no. 8, p. 1011–1012.

The city of Fresno, Calif., disposes of its treated sewage effluent by spreading it on farmland for crop use. The average disposal rate is 0.043 foot per day.

Shafer, R. A.

1953. Ground water and used water in basin recharge areas: Indust. and Eng. Chemistry, v. 45, no. 12, p. 2666–2668.

In southern California, in addition to surface runoff and rainfall, sanitary and industrial waste water and unconsumed irrigation water make important contributions to the ground water. These and the disposal of sewage in the ocean are changing the quality of ground waters. Increase in salinity, in percentages of sodium, and in deleterious chemical substances have been observed in localized areas.

Silitch, E. W.

1948. The place of Ranney collectors in the water supply industry: New Hampshire Water Works Assoc. Jour., October, 8 p.

The construction, operation, and installation of Ranney collector wells for induced recharge by infiltration from rivers are described.

Simpson, H. E. *See* Norton, W. H., 1912.

Simpson, T. R.

1948. Recharge by percolation wells, Excerpts from report on percolation, Feather River and tributaries, counties of Sutter and Yuba, California: California Div. Water Resources, 4 p.

Factors affecting recharge rates in percolation wells include: water to be recharged must be clear and free of bacteria; wells must be fully developed at time of construction; wells should be surged frequently to prevent obstruction of perforations; wells should not be located in quicksand areas; recharge rates will approximate 25 percent of pumping rates when head above the water table equals drawdown. It is proposed to have 250 recharge wells in Feather River, Calif.; with a spacing of 500–1,000 feet between wells, 15,000 acre-feet of water could be recharged in 6 months. The project cost is estimated at $1,000,000.

1952. Utilization of ground water in California: Am. Soc. Civil Engineers Trans., v. 117, p. 923–934.

Artificial recharge by spreading in Santa Clara and Alameda Counties, Calif., is mentioned.

Slater, W. R.

1953. Underground strata recharging: Water Well Jour., v. 7, no. 2, p. 12, 14, 18, 20, 22, 24.

In a general discussion of artificial ground-water recharge, well-recharge program at Manhattan Beach, Calif., is described. A line of nine 12-inch wells were drilled, alternate wells to be used for recharge and the others for observation. In addition, 36 8-inch observation wells surround the recharge line. The purpose of the investigation is to determine if a pressure ridge could be created within a confined aquifer by means of injection wells, and to find if such a ridge would prevent sea-water intrusion.

Sniegocki, R. T. *See also* Steinbruegge, G. W., 1954.

1953. Plans for the first year's work on the artificial recharge project, Grand Prairie region, Arkansas: U. S. Geol. Survey open-file rept., Little Rock, Ark., 16 p.

This project proposes to evaluate the potentialities and limitations of artificial recharge through controlled experiments in the Grand Prairie region, Arkansas. Artificial recharge will be attempted through a regular screened well, a gravel-packed well, and a well consisting of a caisson sunk to the permeable deposits and from which screens radiate into the deposits. Water used would be raw turbid water, raw water that has passed through a settling basin, filtered water, chlorinated water, filtered chlorinated water, and completely treated water. The study would also include behavior and movement of the water beyond the recharge units, bacterial pollution, and a review of the geology and hydrology or the region.

The first year's work on the project would provide the basic data required to pursue the study successfully. Plans cover a review of existing data in the Grand Prairie region, a complete well inventory, pumping tests, test drilling, and preparation of geologic and ground-water maps and profiles.

Sonderegger, A. L.

1918. Hydraulic phenomena and the effect of spreading of flood water in the San Bernardino Basin, Southern California: Am. Soc. Civil Engineers Trans., v. 82, p. 802–851.

Conservation of floodwater by spreading has been practiced on the Santa Ana River alluvial cone near San Bernardino, Calif., since 1900. The method consisted of plowing the stream bed, thereby preventing sealing of the soil pores and at the same time splitting up the stream.

Three methods of spreading are now in use. The first method involves diverting water from the main diversion ditch into small streams and then into furrows. As long as no erosion takes place in the furrows, the absorption rate is satisfactory. During 1915, 120 to 170 cfs were spread by diversion over a wetted area of about 50 acres. Experiments showed the recharge rate to be 6.77 feet per day. The second method consists of building boulder dams in old channels to form small reservoirs or ponds. They are built 6 to 10 feet high and are made relatively impermeable by the addition of earth. In 9 ponds totaling 2 acres in area the initial recharge rates amounted to 18 to 20 feet per day. This rate decreased with silt accumulation, so that at the end of each season they had to be scraped. A third method, tried experimentally, consisted of recharging water down a 5x5-foot timbered pit, 40 feet deep. Only clear water was admitted, but the rate did not exceed 0.7 cfs.

Calculations are made to determine the net artificial recharge, this being the difference between the total amount recharged and the natural recharge. For the 1912 to 1915 seasons it was found that about 50 percent of the total water spread was net artificial recharge.

The benefits of water spreading are that the underground water storage is increased and that spreading of water higher on the alluvial cone than would normally occur increases the length of time that underflow is stored.

1936. Remarks on water-spreading: Am. Geophys. Union Trans., v. 17, pt. II, p. 474-476.

The results of several water-spreading studies in California are reviewed briefly. Percolation rates may be expected to vary widely in different localities because of differences in controlling factors: permeability, vegetal cover, depth to water table, terrain slope, and silt content and composition. Spreading ditches can be used to spread muddy floodwaters if they are designed to regulate velocities so as to avoid silt accumulation.

Soyer, R.

1947. La réalimentation des nappes aquifers (Recharge of aquifers): Technique Sanitaire et Municipal, v. 42, no. 9-10, p. 58-69.

Artificial recharge has been practiced since the end of the 19th century in Europe and more recently in the United States. In France, where ground water was formerly abundant, intensive pumping has caused a decline of water tables. Some water levels cannot be raised by recharging, but where the water table fluctuates with the seasons, recharge is feasible.

Stearns, H. T.

1930. (and Robinson, T. W., and Taylor, G. H.). Geology and water resources of the Mokelumne area, California: U. S. Geol. Survey Water-Supply Paper 619, 402 p.

This paper includes a discussion of ground-water recharge by irrigation methods.

1934. Future ground-water supplies for Honolulu, Hawaii: U. S. Geol. Survey open-file report (mimeo.).

Describes use of a 100-foot deep shaft to dispose of 70 cfs of dirty wash water on the Minidoka irrigation project in Idaho. Similar use of shafts is suggested for Hawaii. Oahu Sugar Company dumped waste irrigation and streamflow water into a tunnel at Kaipahu, thereby increasing the artesian supply.

1938. (and Crandall, L., and Steward, W. G.). Geology and ground-water resources of the Snake River Plain in south-eastern Idaho: U. S. Geol. Survey Water-Supply Paper 774, 268 p.

In the Minidoka area, Idaho, a large sump is used to dispose of surface water underground. It is 6 feet in diameter, about 90 feet deep, and located in basalt and red clinkery lava formations. Water enters the pit after passing through a settling tank and a wooden screen. For years it has been taking an inflow of 22 cfs; above this rate it begins to fill. The bottom of the pit is above the main water table. Other than the cleaning out of leaves and sticks occasionally, the pit requires no attention.

1939. (and Bryan, L. L., and Crandall, L.). Geology and water resources of the Mud Lake region, Idaho, including the Island Park area: U. S. Geol. Survey Water-Supply Paper 818, 125 p.

Because of the high permeability of lava formations in the Mud Lake region, Idaho, wells can be used for surface drainage. Near Market Lake seven wells were drilled for drainage before 1922. Although not maintained, one well was draining one cfs and another 0.25 cfs in 1929. A 6-inch well 151 feet deep drilled in the same area in 1929 drained slightly over 1 cfs.

Steinbruegge, G. W.

1954. (and Heiple, L. R., Rogers, N., and Sniegocki, R. T.). Ground water recharge by means of wells: Fayetteville, Arkansas Univ. Agr. Expt. Sta., 119 p.

This publication is a report of an extensive investigation to determine the status of knowledge concerning artificial recharge of underground reservoirs as it might affect the proposed ground-water recharge project in the Grand Prairie region of Arkansas. In a summary of the investigation, the basic methods of recharge, important recharge projects, base exchange, quality of recharge waters, recharge rates, and construction and operation of recharge wells are discussed.

The second section is a report on results of visits by a field party to selected ground-water recharge projects in the United States. At Richmond, Calif., the underground pollution travel investigation of the University of California was visited. Here studies of injection of treated sewage into a recharge well are underway. The project is described and the most important conclusions are: that heavy concentrations of coliform organisms are readily removed in a very short distance in a normal aquifer, that coliform penetration did not increase with increased length of recharge periods, that clogging of the aquifer near the well can be overcome by redevelopment of the well, and that recharge wells need to be gravel-packed. The Manhattan Beach Project, Los Angeles, Calif., involving recharge in a line of 9 wells to stem sea-water intrusion, was visited and is described. At El Paso, Tex., recharging a well has not caused clogging or collapse of the well, practically all the water recharged can be effectively recovered at a later date, there is no chemical incompatibility of natural and recharged waters, and in this case the well could be recharged at nearly the same rate as it is normally pumped.

Mr. William Guyton, at Austin, Tex., described the Louisville, Ky., recharge program. In redeveloping a recharge well he suggested use of conventional pumping and surging, the pumping to be at a higher rate than the recharge rate, use of water jets under about 200-pounds-per-square-inch pressure with a calgon and chlorine solution added to the jetting water, or use of conventional acid treatments and calgon or detergent treatments. He also suggested that

observation wells be placed very close to the recharge well, that protective maintenance be given priority to avoid head loss during recharging, that water flood or pressure application as practiced in the oil industry be studied, and that open rather than shutter screens were preferable for recharge wells. The final visit was to the King Ranch Project near Kingsville, Tex., where attempts are underway to recharge a deep aquifer of relatively low permeability by means of a well. Filter difficulties and well development have impeded satisfactory operations. Information collected shows that a recharge well operating under these field conditions requires water which has been adequately filtered and treated, that the recharge rate should be less than (possibly less than half) the pumping or redeveloping rate, that it is economically feasible to treat recharge water, and that the open type well screen is superior to the shutter variety for jetting operations.

The remaining two-thirds of the report contains an annotated bibliography on ground-water recharge. Although selected references dealing with recharge wells are summarized in more detail, the bibliography covers recharge by means other than wells.

Steward, W. G. *See* Stearns, H. T., 1938.

Stokes, C. M.

1954. (and Larson, F. D., and Pearse, C. K.). Range improvement through waterspreading: Washington, U. S. Govt. Printing Office, 36 p.

This report presents detailed descriptions and examples of water-spreading on agricultural lands to halt gully erosion, conserve moisture, restore productivity of valley lands, and increase forage supplies. Although the emphasis is not upon ground-water recharge, the information regarding selection, preparation, operation, improvement, and maintenance of spreading areas applies equally for this purpose.

Stone, Ralph. *See also* Jordan, L. W., 1949; Rawn, A. M., 1953.

1952. (and Garber, W. F.). Sewage reclamation by spreading basin infiltration: Am. Soc. Civil Engineers Trans., v. 117, p. 1189-1217.

The feasibility of recharging ground water with effluent from sewage treatment plants was studied by experimental spreading basins at Whittier and Azusa, Calif. Details of the spreading basins, and the effects of climate, soil characteristics, type of spreading fluid, and recharge rates are presented. On the basis of the experimental data it is concluded that percolation rates as high as 1.2 feet per day can be maintained for several months, that for best results basins should be operated intermittently, drying and cultivating scheduled between effluent spreading periods, and that water of good-quality is produced 7 feet below soil surface.

1953. Land disposal of sewage and industrial wastes: Sewage and Indust. Wastes, v. 25, no. 4, p. 406-418.

Sewage and industrial wastes can be disposed of by intermittent irrigation of crops such as grasses and cotton or by intermittent spreading on basins. Field tests at Whittier and Azusa, Calif., showed continued recharge rates of 1.0 foot per day and demonstrated that water of a quality suitable for drinking can be produced by percolation through 3 to 7 feet of surface soil. The average application rate of treated sewage for several California cities employing irrigation for land disposal is 0.034 foot per day. Various factors affecting recharge rates

are discussed and tables show ranges of disposal rates for various soils, methods of disposal, and BOD concentrations.

1954. Infiltration galleries: Am. Soc. Civil Engineers Proc., v. 80, no. 472, 12 p.

Infiltration galleries as a means of collecting ground water from nearby surface-water sources, and limitations, advantages, types, installations, and construction details are described. Information on 33 installations, based on survey data and search of the literature, is presented in tabular form. Eleven of 18 installations surveyed have been abandoned.

Stone, R. V.

1952. (and Gotaas, H. B., and Bacon, V. W.). Economic and technical status of water reclaimed from sewage and industrial wastes: Am. Water Works Assoc. Jour., v. 44, no. 6, p. 503-517.

Various sewage spreading tests have been conducted in California to study recharge rates and pollution travel. At Azusa and Whittier oxidized effluents could be percolated at rates of 0.5 and 2 feet per day, respectively, including 50 percent of the time for pond drying. At Lodi effluents percolated at rates varying from 0.10 to 0.60 feet per day. Spading of the test plots approximately doubled recharge rates. In Kern County spreading of irrigation water has been tested. Although scarifying the surface had no effect on rates, addition of cotton gin trash plus turning of the soil increased rates to 14 feet per day. An over-all average of 3 to 4 feet per day was obtained in treated plots, and 0.5 to 1 foot per day in untreated plots. Grasses grown in ponds have also increased rates. In the Lodi test coliform bacteria were never observed at depths greater than 4 feet.

Costs of reclaimed water at 3 locations in California have been estimated at $9.00 to $20.00 per acre-foot on a 40- to 50-year basis.

Stramel, G. J. *See* Ferris, J. G., 1954.

Stramler, J. H.

1948. Interim report 1947 operations, Madera water spreading: Merced, Calif., U. S. Bur. Reclamation, (mimeo.), 36 p.

A detailed report is presented on experimental recharge operations near Madera, Calif., in 1947. The 6-acre area was divided into strips for studying effects of different treatments on recharge. A total of 23 strips, 602 feet by 14 feet, were laid out. The strips were leveled to a slope of 0.2 foot per 100 feet. Water was spread for 6 weeks, followed by a 3-week drying period, and a final 3-week spreading period. Strip treatments and recharge rates in feet per day are tabulated below:

Treatment	Recharge: Initial rate (feet per day)	Recharge: Final 3 weeks (feet per day)	Recharge: Mean for 2d period (feet per day)
Corn stalks disked under	9.3	2.6	4.1
Harrowed	8.3	1.6	3.1
Cotton balls, disked under	9.3	2.1	2.6
Bermuda grass	3.6	1.6	
Weeds disked under; harrowed	8.3	2.1	
Corn stalks and ammonium sulfate	7.7	1.0	3.1
Harding grass	1.6	1.0	
Weeds disked under; harrowed	4.1	1.6	

Stringfield, V. T. *See also* Sayre, A. N., 1948.

1933. Ground-water investigations in Florida: Florida Geol. Survey Bull. 11, 33 p.

Drainage wells in Orlando and vicinity are used for disposal of sewage and runoff. Approximately 120 wells ranging from 160 to 800 feet in depth and from 6 to 12 inches in diameter are in use. The wells extend into the Ocala limestone and a number of them are cased. Drainage capacity of the wells ranges from less than 0.2 to 21 cfs. The effectiveness of a drainage well depends upon the permeability of the formation into which it discharges, the size and construction of the well, and the depth of the static water level below the surface intake.

1936. Artesian water in the Florida peninsula: U. S. Geol. Survey Water-Supply Paper 773-C, p. 115-195.

More than 120 drainage wells in and near Orlando, Orange County, Fla. (p. 161-162), dispose of sewage and storm runoff. Wells range from 6 to 16 inches in diameter, 160 to 800 feet in depth, and have recharge capacities of less than 0.22 cfs to 21 cfs. The water table varies from a few feet to 60 feet below ground surface.

1945. Effect of air conditioning demand on well water availability: Heating and Ventilating, v. 42, no. 6, p. 61-66.

In order to prevent serious overdraft of the ground water because of excessive pumping for air conditioning, artificial recharge is practiced in several localities. Recharge operations in California and Florida are mentioned, and those on Long Island and Louisville, Ky., are described briefly.

Stuart, W. T. *See also* Guyton, W. F., 1944.

1944. The ground-water investigation at Louisville, Kentucky: The Kentucky Engineer, v. 6, no. 3, p. 18-22.

This article presents a discussion of the overdraft of ground water at Louisville, Ky., and suggests that induced infiltration from the Ohio River and artificial recharge through wells with river water are favorable methods for increasing ground-water supplies.

1945. Conservation of ground water, including artificial recharge, at Louisville, Kentucky: Cast Iron Pipe News, v. 11, no. 1.

Ground-water overdraft conditions at Louisville, Ky., are described. Industrial pumping from private wells in summer and use of municipal water and recharging wells in winter is suggested as a possible solution of the problem.

Sundstrom, R. V.

1952. (and Hood, J. W.). Results of artificial recharge of the ground-water reservoir at El Paso, Texas: Texas Board Water Engineers Bull. 5206, 19. p.

Treated surface water at the Montana well field was injected into four wells spaced 1,500 feet apart, at a total rate of about 9 cfs for an indefinite period. At the Mesa well field, water could be injected at many times the rate possible in the Montana well field. Recharge reduces chloride concentrations below ground; therefore it is assumed that continued recharge will retard or halt salt-water encroachment. From the difference in sulfate content of recharge and ground waters, it is estimated that 95 percent of recharge water was recovered after 271 acre-feet had been injected and 705 acre-feet had been repumped.

Suter, M. *See also* Horberg, L., 1950.

1943. A pilot study of ground-water resources in Peoria County, Illinois: Am. Geophys. Union Trans., v. 24, pt. II, p. 493-500.

As part of a general investigation of ground-water resources near Peoria, Ill., the possibilities of artificial recharge of ground water were explored. Recharge through a well was tried at one location, but the high-iron content of the aerated water used caused the well to clog in about a month. Wells were considered not practical for large-scale infiltration.

A detailed investigation of recharging river water into an abandoned gravel pit was completed. Test wells were located around the pit and arrangements were made to obtain water temperatures and samples from other nearby wells. Water was pumped into the pit at the rate of 4.6 cfs for several days in each of three tests. The infiltration rate from the gravel pit was found to be 113 feet per day. Percolation out of the pit was determined by studying the chloride content in nearby wells after dissolving 5 tons of salt in the pit. Bacterial contamination could be followed for more than 420 feet, although all water pumped into the pit was chlorinated.

A firm of consulting engineers recommended to the Peoria Association of Commerce that artificial recharge be done by land-flooding with pumped river water. This was considered to be the most economical method, being cheapest in initial cost, although somewhat higher in operating cost. None of the proposed methods of artificial recharge have been put into actual practice, mainly because of the hazard of incurring responsibility for pollution of ground water as defined in Illinois law.

1945. Necessity and possibilities for infiltration at Peoria, Illinois: Illinois State Water Survey (mimeo.), 8 p.

To prevent further lowering of ground-water levels at Peoria, Ill., a large-scale artificial recharge program using an infiltration pit is recommended. The pit is planned to cover an area of at least 0.5 acre underlain by gravel covered by a 6-inch layer of sand to act as a rough filter. A recharge rate of 30-60 feet per day is anticipated on the basis of previous tests. Suitability of Illinois River water for recharging is discussed in terms of temperature, turbidity, chemical quality, and sanitary quality. It is concluded that the river water may be recharged when proper conditions prevail. Chlorination will be necessary before recharging.

Suter, R.

1945. Specifications for diffusion wells: New York Div. of Water Power and Control (mimeo.), Albany.

Definitions, regulations, and minimum requirements for diffusion wells on Long Island, N. Y., are discussed.

Tait, C. E.

1917. Preliminary report on conservation and control of flood water in Coachella Valley, California: Calif. Dept. Eng. Bull. 4, 31 p.

Water-spreading operations on Santiago Creek, Santa Ana River, San Antonio Creek, and Lytle Creek are described. Similar practices on Whitewater River are recommended for water conservation and flood control.

1919. Spreading water for flood control, Southern California: Am. Soc. Civil Engineers Assoc. of Members, Bull., v. 1, no. 4, p. 76-86.

This paper discusses in some detail the places to spread water, the character of spreading grounds, and methods of spreading. It also describes water spreading on Santa Ana River, begun in 1903, on Santiago Creek, begun in 1896, on Lytle Creek, where 50-foot shafts were used, and on San Antonio Creek. Selection of methods to be used, works employed in spreading, amounts of water that can be handled, rates of absorption and moisture-holding capacities of grounds, effects of silt on spreading grounds, and costs of spreading water are discussed. It is concluded that water spreading properly conducted is of great economic value in conserving and storing flood water for the benefit of the underground water supply for irrigation. It may be effective as a flood-control measure, independently of conservation, for the smaller streams. For the larger streams, it does not suffice, alone, for flood control, but is of some value in conjunction with other measures such as storage in reservoirs and the use of check dams. FHK.

Task Group E4-B on Artificial Ground Water Recharge

1952. Artificial ground water recharge: Am. Water Works Assoc. Jour., v. 44, no. 3, p. 682-684.

A progress report on artificial ground-water recharge is presented. A total of 110 questionnaires were sent to all water-resource agencies in the United States asking for information on artificial recharge. Of this total, 76 were returned from 45 States. Of the 45 States reporting, only one, New York, requires that water taken from the ground be returned to the ground after it is used. In 4 States recharge was or is practiced on a regional basis, 10 have recharge projects for specific public water supplies, 9 for specific industrial supplies, and 8 for specific irrigation supplies. In the other states reporting, artificial recharge has been limited to one or two projects that are not extensive in size. A majority of the projects are in California and in the eastern seaboard States. Artificial recharge is practiced extensively in areas of sea-water intrusion, of increasing ground-water demand, and of limited water sources. Seven States reported that domestic or industrial waste waters were being used to recharge aquifers, but only one reported use of effluent from sewage- and industrial-treatment plants. Reports from 38 States indicated that there were areas within the states where recharge was not but could be practiced. In reply to questions regarding feasibility of artificial recharge, 6 States reported that some studies had been made, 30 others felt that such studies should be made, and 24 States felt that the practice is likely to be the solution to some of their future ground-water shortages. Two States reported that recharge was being practiced primarily to prevent salt-water intrusion, 4 to conserve water generally, and 26 to solve specific water problems.

Taylor, G. H. *See* Stearns, H. T., 1930.

Thayer, W. N. *See* Jordan, L. W., 1937b; 1937c; 1939; 1940.

Theis, C. V.

1941. The effect of a well on the flow of a nearby stream: Am. Geophys. Union Trans., v. 22, pt. 3, p. 734-738.

Presents a theoretical analysis of a method for computing what portion of water pumped from a well is inflowing from a nearby stream.

Thiele, H. *See* Schneider, H., 1952.

Thiem, A.

1898. Die künstliche Erzeugung von Grundwasser (The artificial production of ground water): Gasbeleuchtung u. Wasserversorgung Jour., v. 41, no. 12, p. 189-193, 207-212.

The practical aspects of the hydraulics of flow from a river to a nearby collecting gallery are discussed comprehensively. Water temperature, bacteria, and clarity are more than satisfactory in most induced recharge installations; temperatures are nearly constant relative to those of the river, bacteria-free water can usually be obtained from river water after percolation through 60 to 130 feet of the sands and gravels of the river valley and clear water can be obtained by percolation through as little as 10 to 12 feet of sand. Contour maps show the effect on the water table of infiltration galleries bordering the Ruhr River at Essen, Germany. An extensive discussion by others completes the paper; problems, examples, and operations of infiltration galleries at other locations in Germany are presented.

Thiem, G.

1923. Wirkung und Zweck von Schluckbrunnen (Effect and purpose of recharge wells): Gesundheits-Ingenieur, v. 46, no. 34, p. 331-333.

The recharge well and its purpose are briefly described. The basic equations for flow from a recharge well are derived from idealized boundary and permeability conditions.

Thomas, H. E. *See also* Piper, A. M., 1939.

1946. Ground-water fluctuations in Utah, 1936-1945: Utah State Engineer, 25th Bienn. Rept., p. 66–89.

This report mentions recharging of water from Pine View Reservoir into old beach deposits of coarse texture along the base of the Wasatch Mountains near Brigham City, Utah, since 1937. Artificial recharge by the cities of Centerville and Bountiful has resulted in locally higher water tables than would have occurred naturally. Induced recharge in Ogden Valley, because of depletion of underground storage during periods of high demand, permits the salvaging of water from Ogden River for beneficial use.

1948. (and W. B. Nelson). Groundwater in the East Shore area, Utah, pt. 1, Bountiful district, Davis County: Utah State Engineer Tech. Pub. 5, *in* State Engineer 26th Bienn. Rept., p. 52-206.

Two water-spreading experiments in the Bountiful district, Utah, are reviewed. (p. 200-205). One involved a spreading basin on the Provo terrace. The other involved diversion of part of the flow of Barton Creek into highly absorptive oak brush areas. *RCV*

1949. Artificial recharge of ground water by the city of Bountiful, Utah: Am. Geophys. Union Trans., v. 30, no. 4, p. 539-542.

Since 1941 the city of Bountiful, Utah, has artificially recharged ground water in an effort to increase well supplies. During the spring season, water from Barton and Stone Creeks is diverted into a 1,200-foot canal from which eleven outlets release the water over a highly absorptive oak-brush area. As much as 425 acre-feet per season have been spread, and there is no evidence that recharge rates have been reduced because of silting. The spreading has caused seasonal water-table rises of more than 15 feet in portions of an area within a half mile west of the canal. It was found that the recharged water did not penetrate to deeper artesian aquifers, but did increase the yield from near-surface strata.

1951. The conservation of ground water: New York, McGraw-Hill Book Co., Inc., 327 p.

Artificial recharge is discussed in connection with areal ground-water problems at Los Angeles, Calif.; Des Moines, Iowa; and Salt River Valley, Ariz. On pages 187-191 the importance of artificial recharge as a conservation measure and general factors affecting recharge rates are discussed.

1952. Ground-water regions of the United States—their storage facilities, v. 3 *in* Physical and Economic Foundation of Natural Resources: U. S. Cong., House Comm. on Interior and Insular Affairs, 78 p.

Various artificial recharge operations in the United States are briefly described. Included are: spreading ponds near Centerville, Utah; spreading areas in Los Angeles County, Calif.; induced infiltration by wells and galleries in midwestern glaciated and unglaciated areas; flooding basins at Des Moines, Iowa; recharge basins at Garden City, N. Y.; well recharge at Louisville, Ky.; sprinkler disposal at Seabrook, N. J.; well recharge at Lindsay, Calif.; and experimental water spreading at Wasco, Calif.

Thompson, D. G. *See also* Engler, K., 1945; Klaer, F. H., Jr., 1948b.

1931. Problems of ground-water supply in Florida: Am. Water Works Assoc. Jour., v. 23, no. 12, p. 2085-2100.

In and around Orlando, Fla., many disposal wells have been drilled into cavernous limestone formations to dispose of surface runoff and sewage. Wells are 6 to 16 inches in diameter, 160 to 800 feet deep, and have capacities of several second-feet. During unusually heavy rains low areas have been flooded owing, it is thought, to the inability of the water-bearing formations to carry off the water as fast as it was supplied.

1941a. Memorandum in regard to artificial recharge of ground water: U. S. Geol. Survey open-file report, 9 p.

This paper contains a general review of methods and results of artificial recharge of ground water and a summary of the important literature on the subject.

1941b. Artificial recharge of ground water: U. S. Geol. Survey, open-file report, (mimeo.), 8 p.

Recharge by water spreading and by wells is discussed briefly. Examples of each method, references to several articles, and data on the Des Moines, Iowa, recharge system for water supply are included.

Tibbetts, F. H.

1931. Report on waste water salvage project: Santa Clara Valley Water Conserv. Dist., 70 p.

As part of a water-conservation plan in Santa Clara Valley, Calif., check dams and spreading dams in stream beds would be used. The possibility of using percolation shafts and tunnels for the treatment of Penitencia Creek water is discussed.

1936a. Supplemental report on completion of the 1934 well replenishment project, including 1931 waste water salvage project: Santa Clara Valley Water Conserv. Dist., Proj. Rept. no. 34.

Cost of construction and operation of partially completed well-replenishment system during season of 1934-35 are discussed. Total inflow into valley was 99,000 acre-feet; wastage was only 28,500 acre-feet instead of the 68 percent that is usual under uncontrolled conditions. Increased storage caused large rises in water levels during 1934-35 and 1935-36.

1936b. Water-conservation project in Santa Clara County: Am. Geophys. Union Trans., v. 17, pt. 2, p. 458-465.

In the Santa Clara Valley Water-Conservation District which includes most of the level floor of Santa Clara Valley, Calif., the construction program has included stream-bed improvements to increase natural percolation rates in stream beds. A few low, buttress-type, concrete-reinforced dams and many sausage dams have been built to increase water-surface areas. Sausage dams are 2½ to 3 feet high, are constructed of Page wire fencing held in place by steel fence posts driven in the gravel creek beds, and cost about $6.00 per lineal foot. It is believed that the higher up on the stream the dams are placed, the wider will be the resulting underground distribution of water. Measured percolation rates range from 2 to 14 or 15 feet per day but are not constant even in the same location. Percolation basins tend to silt up, and are furrowed annually. When water is not impounded to a depth of more than 2 or 3 feet, bottom velocities during floods of most streams are sufficient to scour gravel beds clean again.

Several off-channel water-spreading projects have been developed, consisting of concrete diversion dams for diverting streamflow into canals and hence to areas underlain by gravel where it is ponded for recharge into the ground. The most difficult problem of the project appears to be securing a uniform rise in the water table over the area.

1938a. Experience with ground water replenishment: Am. Water Works Assoc. Jour., v. 30, no. 2, p. 326-334.

The utilization of underground storage in Santa Clara Valley, Santa Clara County, Calif., requires the use of artificial means for increasing natural stream-bed percolation either in the natural stream bed or in off-channel absorption areas. Small dams are useful to create percolation ponds covering a maximum absorptive area. Where recharge rates of 1.5 to 6 or 7 feet per day occur, wire sausage dams 2 or 3 feet in height have been built at a cost of about $7.00 per lineal foot.

1938b. Renewing underground water supply: Eng. News-Rec., v. 120, no. 10, p. 361-365.

The various works constructed in Santa Clara Valley, Santa Clara County, Calif., to replenish ground water are described. Water is recharged by stream-bed reservoirs and off-channel percolation (winter irrigation). Dams have been constructed on some streams to form percolating reservoirs. Water is stored in these reservoirs when the silt content is less than 1 part in 2,000 of silt settling out in 10 minutes. When greater silt content is found, the superstructure is lowered to pass the water and avoid silt accumulation within the reservoir. In other locations wire sausage dams 2 to 3 feet high are constructed to pond water in the channel. These dams can be built for $7 per lineal foot and are

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made from steel cable, steel fence posts, wire mesh, and gravel. Seasonal stream-bed recharge amounts vary between 860 and 1,650 acre-feet per mile. During the natural winter streamflow season, water is diverted by ditches for off-channel percolation. Seasonal recharge rates average from 1.8 to 2.2 feet per day over areas of 17 to 32 acres.

The recharge program has succeeded in increasing underground storage, reducing overdraft, and reducing pumping lifts.

Tison, G.

1954. Un nouveau procédé de captage des eaux souterraines—puits rayonnants horizontaux (A new process for collecting ground water—radial horizontal wells): Technique de l'Eau, no. 85, p. 19-24.

This article describes the design, construction, and operation of a new type of radial collector well for inducing recharge from surface-water sources. The well was developed by Dr. Fehlmann in Berne, Switzerland, in 1947. Its basic design is very similar to that of the Ranney collector. The major difference is in the method of constructing the radial drains. The Ranney method uses a hydraulic press, boring head, and backwashing system to extend the horizontal perforated pipes, whereas the Fehlmann process uses a hydraulic press, drill pipe, and cutting head (pilot). After the horizontal hole is completed, the drill pipe is removed, the cutting head remaining, and the perforated drain pipe of smaller diameter is inserted into the hole.

More than 40 of the Fehlmann collectors have been or are being constructed in Switzerland, Germany, and Italy. Depths average about 30 feet, inside diameters of the central vertical cylinder average 9 feet, outside diameters 11 feet, the number of radial drains averages 8 per collector, and the total length of drains per collector approximates 450 feet. With drawdowns of 3 to 9 feet, the average collector capacity is about 6 cfs.

Todd, D. K. *See also* Klaer, F. H., 1948a.

1953. An abstract of literature pertaining to sea water intrusion and its control: Berkeley, California Univ., Sanitary Eng. Research Proj., Tech. Bull. No. 10, 74 p.

Abstracts in Section III, Injection and Recharge of Aquifers, cover injection wells, chemical composition and treatment of recharge water, effect of recharge water on aquifer temperatures, salt water injection in oil fields, and drainage wells. Section IV, Laboratory and Model Studies, includes material on several model studies for recharge and secondary recovery problems.

Tofte, A. R.

1938. Disposal wells: South Milwaukee, Wis., Excavating Engineers' Publishing Co., The Driller, April, p. 7-10.

The results of a questionnaire sent to all State geologists asking their opinion on the use of disposal wells to return air-conditioning water to the ground where it was obtained showed that almost all were in favor of disposal wells, especially if careful regulations could be maintained to prevent contamination of the returned water.

Tolman, C. F.

1937. Ground water: New York, McGraw-Hill Book Co., Inc., 593 p.

On p. 173-189 is presented a review of artificial recharge. The history of water spreading in California, advantages of ground-water storage, various

methods of spreading, recharge through shafts and wells, and purification by spreading are discussed.

Trainer, F. W. *See* Cederstrom, D. J., 1954.

Trask, F. B.

1903. Water conservation in southern Califronia: The Rural Californian.

An early idea for increasing water supplies by infiltration from canals is described.

Trauger, F. D.

1947. Description of an early experiment in ground-water recharge through wells at Lindsay, California: Stanford Univ., unpublished lecture, 10 p.

To alleviate a water shortage the Lindsay-Strathmore Irrigation District, Tulare County, Calif., embarked upon an artificial recharge program by means of wells early in 1932. Water was diverted from the Kaweah River, screened and chlorinated, and introduced under full pressure head into wells. A total of 1913.7 acre-feet of water was recharged into 75 wells during slightly over a 3-month period. Assuming constant recharge throughout the period, an average rate of about 0.12 cfs was maintained in each well. The largest well capacity amounted to 0.62 cfs for the period. The water table, which was more than 200 feet below ground surface in some places, showed a distinct and appreciable rise with recharge. In some wells the water table rose as much as 52 feet. No cases of well failure or damage were reported as a result of the recharge operations.

Trefethen, J. M.

1949. Geology for engineers: New York, D. Van Nostrand Co., Inc., 620 p.

Mentions, on p. 344-45, methods of artificial recharge, and operations at Des Moines, Iowa, Long Island, N. Y., and Louisville, Ky.

Truelsen, C. *See* Schneider, H., 1952.

Turner, S. F.

1941. (and others). Water resources of Safford and Duncan-Virden Valleys, Arizona, and New Mexico: U. S. Geol. Survey open-file rept. (mimeo.), Tucson, Ariz., 125 p.

Field measurements of seepage losses from unlined canals in Safford and Duncan-Virden Valley, Arizona and New Mexico, indicate that about one-third of the diverted water is recharged to ground water. Losses are greatest in spring, but decrease in summer because of silt deposition. Canals are cleaned in winter by flushing or scraping. On the basis of field experiments, 25 percent of applied irrigation water reaches the ground-water table in these areas. Combined canal and irrigation losses total 50 percent of all diverted water.

1943. (and others). Ground-water resources of the Santa Cruz Basin, Arizona: U. S. Geol. Survey, open-file rept. (mimeo.), Tucson, Ariz., 84 p.

A series of measurements were made of seepage losses from Rillito Creek and Santa Cruz River, Ariz. Rates in various reaches of the creeks ranged from 1.10 to 3.77 feet per day. The data indicated that depth to the water table has an important effect upon infiltration rate. Seepage measurements were also made by determining the rate of lowering of pools remaining in stream

channels after floods. Average rates in the different reaches ranged from 0.31 to 1.20 feet per day. These pools contained a thick cover of silt on the bottom, and the rate of lowering of water levels was apparently inversely proportional to the amount of silt in the pools.

U. S. Department of Agriculture.

1937. Headwaters control and use: Washington, D. C., 261 p.

In a discussion by W. N. White (p. 44-47), artificial recharge of ground water is described in terms of flood control and water conservation. A. T. Mitchelson gives, on pages 184-187, a general discussion of artificial-recharge practices and their applications to runoff control.

U. S. Soil Conservation Service.

1953. Summary of research accomplishments in irrigation and drainage during the period 1945–1953 (mimeo. rept.) : Logan, Utah, 81 p.

This paper describes briefly (p. 7-11) need for, development of, and research on water spreading for artificial ground-water recharge.

University of California, Sanitary Engineering Research Project.

1951. Present economic and technical status of water reclamation from sewage and industrial wastes: Berkeley, Tech. Bull. No. 4, 24 p.

Spreading operations as a means of recharging ground water with reclaimed water are briefly described.

1953a. Annual report on laboratory and field investigations of the travel of pollution from direct water recharge into underground formations: Richmond, Calif., Standard Service Argeement No. 12C-4, 114 p.

This report summarizes a field investigation of the travel of pollution with underground movement of water for the California State Water Pollution Control Board. The field installation, located at the Engineering Field Station of the University of California in Richmond, consists of a 12-inch recharge well 112 feet deep, eighteen 6-inch cased sampling wells located 10 to 500 feet from the recharge well, and appurtenant pipes, pumps, and storage tanks. Recharge of potable water began in February 1952 at a rate of 0.03 cfs. This rate was increased to 0.07 cfs in May 1952 and was maintained until February 1953, when injection of polluted water was begun at the same rate. A buildup in the recharge pressure indicated that the well was clogging owing to organic solids. After 7 weeks, caving around the recharge well resulted in a cross-connection with a second aquifer and in a break-through of injected water to the ground surface.

The study resulted in the following findings: Recharge through a well with treated water is possible for long periods of time without clogging the well. Pollution travel is greatest in the direction of normal ground-water flow. Coliform bacteria were reduced from 106 per 100 milliliters to less than 38 per 100 milliliters at 100 feet from the recharge well. The bacteria traveled 100 feet in 33 hours but no farther thereafter. Aquifers may clog rapidly if water containing an unfavorable proportion of exchangeable ions is injected into an aquifer containing dispersible clay. Organic matter in even small amounts in recharge water may have a serious cumulative clogging effect. Recharge wells should be gravel packed to reduce velocities in the aquifer surrounding the well. They should also be carefully sealed between the well casing and the formation overlying the recharged aquifer to prevent leakage during recharge

or redevelopment. The pressure distribution around a recharge well is the inverse of a drawdown curve. Clogging due to recharge occurs very close to the well face. It was unnecessary to de-aerate the water before injecting.

1953b. Field investigation of waste water reclamation in relation to ground water pollution: California Water Pollution Control Board, Pub. no. 6, 124 p.

This report summarizes an extensive field investigation of water reclamation by sewage spreading. The study was conducted at Lodi, Calif., where eight circular basins, 19 feet in diameter, were constructed with sheet-metal dikes. Four basins were equipped to sample percolating liquid at various depths below ground surface. Studies were made of spreading with fresh water, sewage treatment plant final effluent having a BOD of about 10 ppm, and settled sewage having a BOD of about 100 ppm. It was concluded: that bacteriologically safe water can be produced from either type of sewage effluent if the liquid passes through at least 4 feet of soil; that water of satisfactory chemical quality can be produced from either sewage effluent if high concentrations of undesirable industrial wastes are not included in the raw sewage; that a highly treated sewage plant effluent must be used for spreading in order to obtain high rates of percolation; that a percolation rate of at least 0.5 foot per day can be expected when spreading a final effluent on Hanford fine sandy loam; that the optimum basin operation consists of spreading continuously for about a month, allowing the basin to dry to about the permanent wilting point, cultivating, and then spreading for as long as 6 months before repeating the resting and cultivation; and that mosquitoes and algae may need to be controlled in spreading basins.

1953c. Report on studies of basic parameters of sea-water intrusion and the hydraulics of injection wells; Berkeley, 49 p.

This report discusses hydraulics of sea-water intrusion and injection wells, and model studies to demonstrate and determine the effects of injection and pumping wells on intrusion. Experimental results led to conclusions regarding recharge-well spacing, piezometric heights, and injection rates, as they apply to the control of sea-water intrusion.

1954. Final report on investigation of travel of pollution: Berkeley, 241 p.

This report summarizes a field investigation of travel of bacterial and chemical pollutants and of physical problems involved in recharging aquifers. In the investigation a 12-inch gravel-packed recharge well and twenty-three 6-inch observation wells were utilized. The wells were finished in a confined aquifer approximately 5 feet thick overlain by 90 feet of clay. Equipment was provided for supplying primary settled sewage and fresh water in various combinations for injecting water into the aquifer and for redeveloping the recharge well by pumping. Both fresh water and water degraded with settled sewage were injected at various rates. The rate of travel of recharged water, bacteria, and chemicals were observed. The nature of well clogging was determined, and methods of well redevelopment were studied.

Findings and conclusions from the study include: recharge pressure curves were essentially mirror images of drawdown curves during pumping of the recharge well; recharge pressures of about 70 feet of water could be used safely for operation; recharge can be accomplished at a pressure head similar to the drawdown caused by pumping at an equal rate; clear water can be injected for long periods without difficulty; the injection rate of 0.019 cfs

per foot of aquifer equals the highest rate reported in the literature for successful fresh-water injection; no difficulty with ion exchange resulted; a normal type of gravel-packed well is suitable for recharge; serious clogging can result from dispersion of the clay fraction of an aquifer if excess sodium is introduced; clogging is directly proportional to the amount of solids injected in any period of time; clogging takes place close to the recharge well screen; pumping at moderate rates is not sufficient to remove clogging; gas binding in the aquifer occurred when the temperature of the recharge water was less than the ground-water temperature; injected chlorine reduces well clogging; redevelopment once a week, involving discharge of 4 to 5 percent of the injected water, was necessary to maintain injection rates.

Unklesbay, A. G.

1944. Ground-water conditions in Orlando and vicinity, Florida: Florida Geol. Survey Rept. Inv. no. 5, 72 p.

This report discusses in detail the geology and ground-water condtions in the vicinity of Orlando, Orange County, Fla., where drainage wells have been used for the disposal of storm runoff and septic tank effluent since about 1904. In 1943 at least 182 drainage wells were in operation in Orlando and vicinity: 90 storm drainage wells owned by City of Orlando; 40 storm, swamp, and lake drainage wells owned by Orange County; 12 drainage wells at Orlando Air Base; and 40 privately and municipally owned drainage wells used for various purposes. Wells range in depth from about 120 to 1,000 feet, are cased to depths of 74 to about 400 feet, and range in diameter from 5 to 18 inches. Capacities range from 0.2 to several cfs. Eight wells were explored with a deep-well current meter to locate porous zones at which water was leaving the wells. These wells may possibly pollute supply wells, but such pollution has not been definitely proved. *FHK*

1946. (and Cooper, H. H., Jr.). Artificial recharge of artesian limestone at Orlando, Florida: Econ. Geology, v. 41, no. 4, p. 293–307.

Owing to lack of adequate surface drainage, more than 200 wells have been drilled into the limestones in and around Orlando, Fla., to drain streets, control lake levels, and dispose of sewage and other waste liquids. Wells range in depth from 120 to 1,000 feet, and in diameter from 5 to 18 inches. Well casings range from 67 to 400 feet in depth. Most of the wells have large capacities, one being reported at 21 cfs. A few have capacities as low as 0.2 cfs, but these are exceptional. The limestone is so cavernous that the wells seldom become clogged, although a considerable amount of rubbish is carried into them. The static water table is generally 30 to 55 feet below ground surface and is highest where disposal wells are concentrated.

van der Goot, H. A. *See* Jordan, L. W., 1950; Laverty, F. B., 1951.

Van Norman, H. A.

1934. Research and investigational studies in water works: Am. Water Works Assoc. Jour., v. 26, no. 5, p. 571–578.

The Owens Valley Aqueduct of the City of Los Angeles, Calif., was terminated in San Fernando Valley in order to spread excess water for storage underground. For the water year 1932–33, 31,298 acre-feet of water was spread over 47 acres at an average recharge rate of 6.92 feet per day.

Van Tuyl, D. W.

1948. Determination of stream flow loss caused by ground-water pumping at Canton, Ohio: U. S. Geol. Survey open-file rept.

This report describes analysis of streamflow measurement and seepage runs to determine seepage losses and induced recharge caused by pumping from wells of the northeast well field of the Canton municipal water supply. *FHK*

1951. Ground water for air conditioning at Pittsburgh, Pennsylvania: Pennsylvania Dept. Int. Affairs, Bull. W-10, 34 p.

One method of conserving ground water in the Triangle area of Pittsburgh, Pa., is recharging through wells. Four considerations would be involved in any artificial-recharge plan in the area: availability of suitable recharge water; a coordinated plan by which users would benefit in proportion to their contributions; a program for determining the effectiveness of the recharge; and economic factors which vary among the many well owners.

Verigin, N. N.

1949. On the rise of the level of ground water under the influence of forced infiltration (in Russian); Izvestiya Otd. Tekh. Nauk., no. 11, p. 1723–1734.

A mathematical model in terms of the theory of functions of complex variables is given for the study of a problem on the infiltration of water into soils. The particular problem considered is determination of ground-water level at various points between two bodies of water, such as rivers, if forced infiltration is applied along the ridge of the water divide between the bodies of water. *HPT*

Volk, K. Q.

1934. Maintenance and operating problems of water spreading grounds, Southern California: Am. Geophys. Union Trans., v. 15, pt. 2, p. 527–530.

Several aspects of water spreading in southern California are described briefly, including financing, land types and ownership, types and costs of diversion dams, distribution systems, desilting basins, and operation and maintenance of spreading grounds. Spreading costs for labor and materials averaged $0.153 per acre-foot over 2 seasons for Santa Clara Water Conservation District, Ventura County. Stream-bed percolation rates below several dams in Los Angeles County range from 2.7 to 16.0 feet per day.

Vollmar.

1931. Bericht über Erfahrungen mit künstlicher Grundwassererzeugung (Report on results with artificial ground-water production): Gas- u. Wasserfach, v. 74, no. 35, p. 805–810.

The plant design, layout, and operation of the waterworks for Hosterwitz, Germany are described. The installation is located on the bank of the Elbe River from which the water supply originates. Water is first pumped from the river to settling basins. After about 4 hours 50 percent of the suspended matter has settled out and the water is pumped to rapid sand filters. Passing through the filters at a rate of 33 feet per hour, the water is then discharged into a series of infiltration basins. The recharged water is pumped from lines of

wells on each side of the basins for distribution to the city. Representative water-quality analyses are shown to indicate the effectiveness of the treatment process.

Walter, E.

1945. (and Cannard, R. E.). Ranney type collectors solve Manitowoc's water problem: Am. City, v. 60, no. 9, p. 112–113.

Two Ranney collectors installed at Manitowoc, Wis., capacity 25 cfs, derive water by induced infiltration from Lake Michigan. *FHK*

Waterman, W. G.

1950. Diffusion wells: U. S. Navy, Civil Engineer Corps Bull., v. 4, no. 39, p. 38–40.

A typical recharge well on Long Island, N. Y., extends more than 30 feet below the static water table, the screen is 25 feet long and 16 inches in diameter, and is surrounded by a 30-inch gravel pack. Diffusion wells should be located as far as possible downstream from supply wells and should discharge into the upper portion of the aquifer, whereas supply wells should draw from the lower portion of the aquifer.

The following precautions are useful in obtaining satisfactory operation of diffusion wells: the open area of the diffusion screen should be at least 25 percent greater than that of the supply well; diffused water should be clean, free of silt, and contain a minimum of air; the diffuser effective area (the circumferential area around the screen or gravel) should be at least 100 percent greater than that of the supply well; diffusion rates should not be so large as to cause a ground-water mound which could result in local floodings; diffusion wells require more maintenance than supply wells, hence accessibility and inspection facilities are important; diffusion of excessively hot water may be harmful to an aquifer; diffusion wells should not be expected to handle more than 0.6–0.9 cfs each.

Welsch, W. F.

1949. Conservation of ground-water resources, Nassau County, New York: Water Works Eng., v. 102, no. 8, p. 708–710, 741–746.

To meet the need for increased ground-water supply in Nassau County, Long Island, N. Y., a long-range program of artificial recharge was inaugurated. About 25 basins are planned to store storm water for recharging. To date, 14 of these basins have been constructed. They range in size from 2 to 9 acres and total about 40 acres. Test borings to depths of 20 feet were made at each proposed basin site. Earth embankments with slopes of less than one to two retain the water within the basins. For optimum results the bottom of the recharge basin should be about 10 feet above the static water table. Concrete or timber chutes and baffles were constructed wherever necessary to prevent scouring of the basin floor. Experiments on rate of seepage, based on heads of 0.5 to 9 feet, indicated an average recharge rate of 3.1 feet per day. For design a recharge rate of 1.5 feet per day is used. Basins should be cleaned twice each year to remove silt. Sand should be added whenever necessary to restore the original basin level.

Wentworth, C. K.

1951. Geology and ground-water resources of the Honolulu-Pearl Harbor area, Oahu, Hawaii: City and County of Honolulu, Board Water Supply, 111 p.

To increase water resources for the Honolulu area, recharge tunnels are recommended. Requirements for these will be similar to skimming tunnels in basal rock. The danger from clogging is small.

Weston, R. S. *See* Flinn, A. D., 1927.

Whetstone, G. A.

1954. Mechanism of ground-water recharge: Agr. Eng., v. 35, no. 9, p. 646–647, 650.

A discussion of artificial recharge by surface infiltration with special reference to the effect of presence of gases in pore spaces of the soil. Cites early experiments of Jamin in 1860 on effect of gas bubbles in capillary tubes and correlates the implications of Jamin's experiments to ground-water recharge. States that alternate wetting and drying of recharge areas is to be avoided. Decreasing of soil pore size by clogging with silt is also to be avoided. *GWS*

Whitman, N. D., Jr. *See* Hill, R. A., 1936.

Wills, L. J. *See* Barrows, G., 1913.

Wilson, C.

1930. Los Angeles successfully reclaims sewage for replenishment of underground water supplies: Western Construction News, v. 5, no. 18, p. 473–474.

One phase of the Los Angeles sewage reclamation study will be replenishment of ground water by wells and galleries, water spreading, percolation experiments, purification by filtration from spreading, pollution and chemical transformations with travel underground, and the percentage recoverable in different basins.

Winslow, C. E. A.

1906. (and Phelps, E. B.). Investigations on the purification of Boston sewage: U. S. Geol. Survey Water-Supply Paper 185, 163 p.

One method of sewage disposal consists of distributing the sewage over broad areas and allowing the liquid to recharge the ground water. The method has been widely used in Europe since the sixteenth century. Conditions for "sewage farming" are specially favorable in the arid portions of the western United States. Plants in Utah, California, and Wyoming are mentioned. In areas selected for sewage application the soil should be light and the subsoil sandy or gravelly to obtain suitable recharge rates. Recharge rates in England range between 0.006 and 0.046 feet per day and in Germany between 0.006 and 0.021 feet per day.

Wise, L. L.

1949. The Richland story; Pt II, Artificially recharged wells provide city water: Eng. News-Rec., v. 143, no. 11, p. 42–44.

The water supply for Richland, Wash., is obtained from 3 well fields which are directly recharged through spreading basins. Two of the basins receive water from the Yakima River by means of irrigation canals, and the third basin is supplied by pumping from the Columbia River. The well-field gravels serve as a natural filter and storage system. The average percolation rate is 7.7 feet per day. During the first year of operation the recharge rate gradually

decreased because of silting and algal growth. At the end of the summer season the basin was cleaned by scraping the surface with a bulldozer. When the basin was reflooded, the rated capacity developed shortly. Yakima River water for recharging is now being treated with copper sulfate in an effort to reduce algal growth. If this is not sufficient to reduce clogging some form of presedimentation may be adopted.

Wisler, C. O. See Ferris, J. G., 1949.

Wolber, J.

1941. Erfahrungen beim Ausbau eines Wasserwerks mit Oberflächen- und Grundwasserversorgung (Experience with the development of a water-works with surface and ground-water supplies): Gas- u. Wasserfach, v. 84, no. 17, p. 257–263.

This report describes a water supply system in West Germany along the Ruhr River in which formerly only surface water was used, but which now includes ground water. The new system involved dredging a small stream to form an infiltration basin, installing a collecting gallery, and installing a large well fed by the gallery to pump the water for use. Water quality aspects of the installation are discussed in some detail.

Wolman, Abel

1952. Characteristics and problems of industrial water supply: Am. Water Works Assoc. Jour., v. 44, no. 4 p. 279–286.

One of the problems of industrial water supply is that the use of artificial recharge as a means of conserving underground water supplies has not been rapidly extended. Its importance for industrial purposes cannot be overemphasized, but experimentation with controlled water spreading is not frequent. Stimulation of such undertakings should be one of the major efforts of official agencies. During World War II the War Production Board attempted to initiate similar conservation activities in industry, but the idea received only limited acceptance.

Wood, F. H.

1945. Water for war plants—a high priority product: Civil Eng., v. 15, no. 7, p. 303–306.

This article includes a brief description of recharge of distillery wells with Louisville, Ky., city water in 1944 to meet emergency ground-water shortage.

Wright, J. E.

1941. A report upon the spreading of water for storage underground: Berkeley, California Univ., BS Thesis, 41 p.

Methods of water spreading, economy of maintaining the ground-water supply, value of water spread, and cost of spreading operations are described. The Santa Clara Valley project, Santa Clara County, Shafter-Wasco experimental project, Kern County, and Rio Hondo spreading operations, Los Angeles County, all in California, are reviewed.

Wright, K. K.

1952. Underground water problems in California: Am. Water Works Assoc. Jour., v. 44, no. 8, p. 662–668.

In some areas of California, special districts, such as conservation districts and county water districts, have been organized to purchase or acquire water

from outside sources for the purpose of spreading it. A recent amendment to the Los Angeles County Flood Control District Act of California permits the creation of special assessment or taxing zones for the purpose of acquiring and spreading imported water to benefit deficient areas.

Anonymous

1. 1894. Water purification in America: Eng. News, v. 31, no. 5, p. 83–86.

In 1890 the Citizen's Water Co. constructed 20 acres of ponds along the South Platte River near Denver, Colo. These ponds were located over wooden infiltration galleries and were filled with diverted river water to a depth of about 5 feet. There was 15 feet of sand between the bottom of the ponds and the top of the galleries. The ponds were cleaned annually by drying, by scraping and removing the silt, and by loosening the bottom gravel with a plow. The yield of the galleries more than doubled after construction of the spreading ponds.

2. 1900. Künstliches Grundwasser (Artificial ground water): Gasbeleuchtung u, Wasserversorgung Jour., v. 43, no. 38, p. 718–719.

This article summarizes material presented in the booklet by Richert. (See Richert, 1900.)

3. 1903. An artificial underground water supply at Gothenburg, Sweden: Eng. News, v. 49, no. 2, p. 32–33.

In 1899 J. G. Richert developed a water supply for Gothenburg, Sweden, in which river water is fed to two filter basins constructed 650 feet from the Gota Elf River. The river water is recharged into a confined sand aquifer from the basins at a rate of 4.2 feet per day. The basins are operated alternately, the basin not in operation being cleaned by scraping the sand surface. Water is pumped from a series of 20 wells surrounding the basins.

The water pumped is of satisfactory chemical quality and almost entirely free of bacteria. Mr. Richert believes that all of the water recharged into the aquifer is pumped from the wells, so that no loss occurs.

Mr. Richert outlines a scheme for applying the same method to augment the water supply of London.

4. 1909. Infiltration well at Coshocton, Ohio: Eng. Rec., v. 60, no. 18, p. 497.

A cylindrical well located in glacial drift between two rivers at Coshocton, Ohio, is described. The well is 30 feet in diameter and 32 feet in depth. Water enters the bottom of the well through the gravel and sand at a maximum rate of 285 acre-feet (about 1½ million gallons) per day. It is believed that after 5 years of operation the capacity of the well is slowly descreasing because of silting up of the gravel surrounding the well.

5. 1912. The new filter gallery at Des Moines: Eng. Rec., v. 65, no. 17, p. 468–469.

This article describes construction details of a new infiltration gallery which is located across the Raccoon River from the pumping station. The gallery parallels the river and extends 4,300 feet upstream from a point directly opposite the pumping station.

6. 1922. Flood-control dam replenishes underground water source: Eng. News-Rec. v. 88, no. 19, p. 770–771.

Flood waters stored in the reservoir back of Devil's Gate Dam, Pasadena, Calif., recharge the ground-water supply for Pasadena. Measurements after floods show that percolation rates are proportional to the reservoir water level.

7. 1924. Water conservation program for Los Angeles County: Eng. News-Rec., v. 92, no. 26, p. 1088–1090.

As part of an expanded flood control and water conservation program in Los Angeles County, Calif., it is planned to permit a continuous discharge from San Gabriel Reservoir to recharge ground water through gravel beds. It is estimated that 500,000 acre-feet can be recharged in this manner each season.

8. 1934. Supplementary underground water flow: Public Works, v. 65, no. 7, p. 11–12.

This article summarizes reports on water spreading for artificial recharge at Los Angeles, Calif. (Lane, 1934a.), at Newton, Mass. (Sampson, 1934), and at Dresden, Germany (Riedel, 1934).

9. 1935. A request for information on ground water replenishment: Am. Water Works Assoc. Jour., v. 27, no. 5, p. 662.

Ground-water supplies for Canton, Ohio, are being rapidly depleted. It is proposed to impound the water of Nimishillen Creek in infiltration reservoirs to replenish the ground water. Underlying gravel would be uncovered to promote rapid recharge.

10. 1941. Radial wells for powder plant water supply: Eng. News-Rec., v. 127, no. 5, p. 155–157.

The construction of seven Ranney collector wells along the Ohio River at Charlestown, Ind., is described. The operation will provide a maximum capacity of 109 cfs.

11. 1941. The Ranney system of underground-water collection: Engineering, v. 152, no. 3961, p. 461–463.

The Ranney horizontal collector well, including its design and construction, is described and illustrated. Installations at Canton, Ohio, and Charlestown, Ind., are mentioned as well as one installed at Sunbury Cross in 1934 as part of the London, England, water supply.

12. 1943. Underground channels utilized for airport drainage: Eng. News-Rec., v. 130, no. 14, p. 498–499.

To provide drainage for an airport in the midwestern United States, 12 drainage wells were constructed. The area is in a region of pervious limestone overlain by 15 to 20 feet of dense red clay. Manholes were built at various locations on the airport and 12-inch wells were drilled in the manholes and through the clay for drainage.

13. 1944. Horizontal water wells being successfully used by war industry: Sci. Am., v. 170, no. 1, p. 21.

A Ranney type radial collector well may have 15 cfs capacity per single unit. It consists of a vertical shaft 13 feet in diameter (inside) and 16 feet in diameter (outside). From this shaft horizontal perforated 8-inch pipes extend as far as 300 feet. The number and length depend on amount of water needed and the specific geologic conditions. Well-points have been forced out by hydraulic jack, but the resulting compaction reduced yield. Ranney's special boring head attached to the outer end of a screen pipe enables the fine sand and silt to be removed, thus permitting the formation of a gravel pack around the screen pipe and easy access of the water. *NR*

14. 1945. Conservation of ground water in the Louisville area, Kentucky: Am. Water Works Assoc. Jour., v. 37, no. 6, p. 543–562.

A detailed description is given of recharge through wells by distilleries at Louisville, Ky., in the spring of 1944.

15. 1945. Requirements for diffusion wells in New York State: Water Works Eng., v. 98, p. 638–639.

Since 1937, new wells on Long Island have not been authorized by the New York Water Power and Control Commission unless the water from wells pumping over a certain amount per minute per day was to be returned underground by diffusion (recharge) wells. A conference of well drillers and operators suggested requirements for diffusion-well construction. Recharge wells should have a capacity 25 percent greater than nearby pumping wells. Water has been successfully recharged into dry sand and wet sand. The commission will establish diffusion-well specifications for the state.

16. 1946. Reclaimed sewage to replace ground water in Los Angeles area: Civil Eng., v. 16, no. 11, p. 498.

One possible source of additional water in Los Angeles, Calif., is purification of sewage and injection underground through wells. Recharge wells would in no case be closer than 1,000 feet to pumped wells, and the circulated water would be completely purified.

Recharge rates of 2 cfs per well were assumed; however, at only half-time operation of each well, an average of one cfs would be recharged. A total of 80,000 acre-feet of water could be replenished in this manner with 110 recharge wells.

17. 1947. Legislative protection for Indiana ground waters: Am. Water Works Assoc. Jour., v. 39, no. 6, p. 527–528.

This article presents text of an act passed by the Indiana Legislature requiring that water pumped from wells at rates exceeding 200 gpm and being used for cooling or air-conditioning (a) be reused, (b) be recharged into the ground by means of wells, or (c) be wasted only by permit from the Indiana Department of Conservation.

18. 1947. Three ground-water articles given at N.E.W.W.A. meetings: Water Works Eng., v. 100, no. 22, p. 1309, 1324–1326.

Ranney collectors installed at Wallingford and Rocky Hill, Conn., are described. They obtain water by induced infiltration from the Quinnipiac River and Connecticut River, respectively.

19. 1947. Ventura County ground water lowers: Western Construction News, v. 22, no. 12, p. 74–76.

Saticoy and Piru spreading grounds in Ventura County, Calif., are described. Recharge rates in the Saticoy spreading basins average 3 acre-feet per day per acre of wetted area.

20. 1948. Anderson uses horizontal well supply: Am. City, v. 63, no. 4, p. 97–98.

Four Ranney collectors at Anderson, Ind., which obtain water by induced infiltration from Killbuck Creek are described. The system will yield about 19 cfs.

21. 1948. Good to the last drop: Am. Water Works Assoc. Jour., v. 40 no. 7, p. 2, 4.

The experimental well-recharge program underway at Newark, N. J., is described.

22. 1948. Ground water problems were featured at Atlantic City: Water Works Eng., v. 101, no. 6, p. 542.

Papers on recharge operations and effects of recharge on Long Island, N. Y., are summarized.

23. 1948. Newark, N. J., experimenting with ground-water recharge: Water Works Eng., v. 101, no. 11, p. 1080.

Ground-water pumpage around Newark, N. J., has seriously lowered water levels and induced salt-water intrusion from a tidal river. The city has permitted a large brewery to return water underground through five wells to determine the feasibility of recharge. A maximum rate of 3 mgd is reported. If the method is successful, cold water formerly wasted might be stored underground for later use.

24. 1948. Protection of ground water on Long Island: Public Works, v. 79, no. 6, p. 48.

This article contains a brief summary of the recharge program on Long Island, N. Y., under the direction of the New York State Water Power and Control Commission.

25. 1948. Water spreading and conservation: Water and Sewage, v. 86 no. 7, p. 19, 21.

This is an editorial describing and recommending water spreading as an integrated solution for flood-control and water-conservation problems. Water-spreading operation at Moose Jaw, Canada, is mentioned.

26. 1949. Nature gives Canton a helping hand: Mueller Rec., May-June.

At Canton, Ohio, a radial recharge well takes water from a shallow upper aquifer fed from a nearby stream and recharges it into a deeper aquifer which is the source of the city water supply. Three such wells were constructed, two for recharge and one for pumping.

27. 1949. Reclaiming water from sewage: Public Works, v. 80, no. 10, p. 56–58.

A report to the Los Angeles County Sanitation Districts on the feasibility of reclaiming sewage is summarized. To establish a procedure for spreading sewage for ground-water recharge, a test basin was prepared and operated with an oxidized, stable secondary sewage effluent. The soil to a depth of 4½ feet had an effective size of 0.44 mm and uniformity coefficient of 4.25–4.00. From 4½ to 6 feet the effective size was 0.090 mm and the uniformity coefficient was 3.60. Experimental data indicated that the effluent may be recharged for 7 consecutive days at an average rate of 1 foot per day, and during the following 7 days the basin should be dewatered, dried, and cultivated. Samples of water collected at depths of 4 to 7 feet below the bottom of the recharge basin showed an absence of pollution, indicated by a zero coliform index and the existence of aerobic conditions at all depths. To estimate the spreading area necessary for continued successful recharge, an average rate of 0.5 foot per day was assumed for each 2-week period. When sewage spreading is combined with flood-water spreading, there must be sufficient pumping draft on the area to maintain the water table at least 25 feet below basin beds during the wet cycle in order to permit the required high rate of flood-water spreading.

28. 1949. Underground water discussed at New Jersey section meeting: Water Works Eng., v. 102, no. 1, p. 39–41.

Papers on recharge methods and well construction are discussed.

29. 1951. Fill 'er up!: Indus. and Eng. Chemistry, v. 43, no. 6, p. 11A, 13A.

The infiltration pit at Peoria, Ill., for recharging depleted ground water is described briefly. The pit was formed by digging 35 feet to gravel and sand strata, of which a horizontal cross section 75 feet square was exposed. Chlorinated water from the nearby Illinois River will enter the pit by gravity flow. Operation will be on a half-time basis. Periods of lowest river temperatures will be selected for recharging to supply the coldest possible water for industrial consumption. An annual average recharge rate of 1.5 cfs is anticipated, which amounts to roughly one-sixth of the annual average deficiency in the area.

Initial capital investment for the pit, including retaining walls, feed channel, and chlorination works, is about $100,000; operating costs are expected to approximate $25,000 per year initially, with the possibility of reductions to half that amount, or less.

30. 1952. Ground-water recharge works well in Texas: Eng. News-Rec., v. 149, no. 6, p. 62.

Artificial recharge with treated Rio Grande water is under study to control salt-water encroachment underground. Water is recharged through wells at a rate as high as 2.3 cfs per well.

31. 1952. Pouring it back: Indus. and Eng. Chemistry, v. 44, no. 3, p. 18A, 20A.

This article describes creation of the High Plains Underground Water District No. 1, covering 13 West Texas counties, for the purpose of artificially recharging ground water. Under ultimate development, more than 4 cfs will be recharged by use of spreading areas, recharge wells, and pits. Experimental tests have shown that recharge wells can be successfully operated. The most serious problem anticipated is the buildup of mineral concentration with time due to the water recirculation that will be established.

It is conceivable that application of the soil conditioner Krilium to the tight soils in the region would produce a porous and granulated topsoil. This would allow rapid rainfall absorption, would reduce wastage by runoff and evaporation, and perhaps would make recharging unnecessary.

32. 1953. Ground water supplies said unaffected by cooling water: Eng. News-Rec., v. 150, no. 13, p. 43.

A study at Fresno, Calif., shows that in 8 years the return of air-conditioning or refrigeration-cooling water to the ground-water table neither pollutes the water nor appreciably raises its temperature.

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