STUDIES IN
WATER RECLAMATION

SANITARY ENGINEERING RESEARCH LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY

STUDIES IN WATER RECLAMATION

Sanitary Engineering Research Laboratory

Department of Engineering

University of California

Berkeley

July 1955

Technical Bulletin No. 13
I.E.R. Series 37

Price $1.00

SANITARY ENGINEERING RESEARCH LABORATORY

UNIVERSITY OF CALIFORNIA

University Officials

Robert G. Sproul, President of the University
Morrough P. O'Brien, Dean of the College of Engineering, Berkeley
Harold B. Gotaas, Director, Sanitary Engineering Research Laboratory and Professor of Sanitary Engineering
Henry A. Schade, Director, Institute of Engineering Research

Faculty Committee

Harold B. Gotaas, Professor of Sanitary Engineering
Wilfred F. Langelier, Professor of Sanitary Engineering
Erman A. Pearson, Associate Professor of Sanitary Engineering
Frederick L. Hotes, Associate Professor of Irrigation Engineering
Warren J. Kaufman, Assistant Professor of Sanitary Engineering
Gerald T. Orlob, Assistant Professor of Civil Engineering
Bernard D. Tebbens, Associate Professor of Industrial Hygiene
Edwin S. Crosby, Assistant Professor of Public Health and Sanitary Science

Research Staff

Ann Bolles, Microbiologist
Henry Gee, Chemical Engineer
Clarence C. Golueke, Sanitary Biologist
Frank B. Hicks, Entomologist
Gerhard Klein, Chemical Engineer
Stephen A. Klein, Food Technologist
M. Beverly Kole, Secretary
Ray B. Krone, Soil Scientist
Leung-ku Lau, Hydraulic Engineer
P. H. McGauhey, Sanitary Engineer (Assistant Director)
William J. Oswald, Sanitary Engineer
Jean Pugsley, Typist-Clerk
Jerome F. Thomas, Chemist
Theodore R. Weller, Sanitary Scientist
Curtis R. Wherry, Soil Scientist
Francis F. Wong, Zoologist

CONTENTS

LIST OF FIGURES

LIST OF TABLES

PREFACE

Need for Studies

The water resources of California have often been considered the factor most likely to limit its future growth and prosperity. Such a possibility is indeed easy to envision when an appraisal is made of the water supply problems which have accompanied the State's phenomenal population growth from 6.9 to 10 million in the period of 1940 to 1953, especially when consideration is given to the prospect of 20 million inhabitants by the year 1975. The increasing demand for water by California's growing population and agriculture has been met in the past essentially by two devices — importation of surface water from more remote areas, and exploitation of ground water reservoirs at an ever accelerating rate. Both of these devices have unpleasant implications for the future.

It is expected that in 1975, 13 of the State's 20 million inhabitants will be concentrated in its two largest metropolitan areas. Their demand for water, as well as the irrigation water needs of the Central Valley and other fertile areas, inevitably means that ever greater importation of water must be practiced, both because of the geographical separation of population centers and sources of surface water, and because of a catastrophic depletion of local ground water supplies. At the same time, competition for importable water will become more intense as local interests, seeing water as their own hope for future prosperity, increase their resistance to efforts to appropriate it for use elsewhere.

Overdrafts on ground waters have already produced serious consequences. In some cases the effect thus far has been limited to economic loss as ground water users have been obliged to drill deeper and deeper into the earth and to provide more expensive well equipment subject to greater power costs. In the upper Santa Clara Valley, for example, farmers who once drove well points into water bearing strata eight or ten feet below the ground surface are now drilling 200 feet, only to watch the water table go down farther year by year. Again in the Mendota-Huron area west of Fresno (1) the annual decline in the water table since 1945 has averaged 4 to 7 feet in the north end of the basin and 20 to 30 feet in the south end. Over a vast area 71 miles in length the decline in the water table has ranged from 150 to 300 feet, mostly since 1940. The net overdraft producing such a decline amounted to 350,000 acre feet in 1950-51. Its increase to 740,000 acre feet in 1952-53 is exemplary of the rate at which ground water resources are being depleted by over pumpage.

Better known perhaps is the situation in the West Coast Basin where a water table which once overflowed in artesian springs is now as much as 15 feet below sea level as a result of an annual average overdraft estimated at some 60,000 acre feet. The West Coast Basin, however, is probably far from being the most impoverished of the group of basins in California having a total overdraft in the order of 2,000,000 acre-feet annually.

Accompanying the decline in ground water table in the Los Angeles area is an intrusion of sea water. In the vicinity of Manhattan Beach the aquifer is being lost as a source of local water supply because of intruding saline waters now extending as much as 2 miles inland from the ocean beach. Banks and Richter (2) noted in 1953 that there is definite evidence of serious intrusion into twelve additional basins and at least seven others are endangered. In all, some 80 major and minor ground water basins in California have already been invaded or are in immediate potential danger of invasion by sea water.

The onset of the foregoing and other equally well known water problems in California, together with increasing water pollution, can only mean that the search for new sources of water must inevitably lead to the reclamation of waters generally considered as waste products of our cities and industries, as well as of other waters for which there exists no economical techniques for reclamation. This fact suggested to members of the staffs of various state agencies including the University of California, that exploration of methods and problems of water reclamation should be initiated immediately through appropriate research.

Purpose of Report

It is the purpose of this report to review the general progress that has been made in the past few years toward a solution to the problems of waste water reclamation, and especially to report the specific findings of the Sanitary Engineering Research Laboratory of the University of California in the course of investigations financed by various public agencies and by the University itself.

The results of some of the studies made by the University and herein reported have been previously presented in formal reports to sponsoring agencies but have not been published for general distribution. Reports on other studies have appeared as bulletins, or are scheduled for publication as bulletins by the University of

California or by the California State Water Pollution Control Board. Several investigations conducted for purposes other than water reclamation have made significant contributions to the subject. It is the intent of this report to bring together for the first time the pertinent results of these various investigations so that they may be more readily available to others interested in the subject of water reclamation.

For the purpose of the report the term "waste water" is used in a broad sense to include waters which in the absence of specific reclamation procedures are now generally wasted, as well as waters which are presently rejected because they carry objectionable amounts of domestic and industrial wastes or high concentrations of dissolved chemicals.

Organization for Studies Reported

The principal investigations on which this report is based were conducted by the Sanitary Engineering Research Laboratory of the University of California, under the direction of Professor Harold B. Gotaas. The report was prepared by P. H. McGauhey and reviewed by Professor W. J. Kaufman and Professor H. B. Gotaas.

Investigations conducted by the Laboratory with funds supplied by the University and by various state and federal agencies contracting with the University, scheduled for early publication and dealing directly or indirectly with the subject of water reclamation, include: A study of pollution travel and other aspects of direct ground water recharge (3) (4), sponsored by the California State Water Pollution Control Board; a study of sea water intrusion into underground aquifers (5), sponsored by the California State Water Resources Board; and an investigation of sewage spreading on California soils (6), sponsored by the University of California. Previously reported but unpublished work included studies of radioactive waste disposal (7) (8) (9), sponsored by the Atomic Energy Commission. Investigations which have resulted in numerous technical articles and reports, to which reference is made in the proper place in this report, include: studies of sewage treatment by photosynthesis, sponsored jointly by the University of California and the Public Health Service; and a number of extensive studies of sea water reclamation by Professor W. F. Langelier, under University and War Department sponsorship. Previously published reports include a study of water reclamation by sewage spreading at Lodi, California (10) sponsored by the California State Health Department, the California State Water Pollution Control Board, and the University: an abstract of literature on sea water intrusion (11), prepared for the California State Water Resources Board; and a review of the economic and technical status of water reclamation (12), sponsored by the University.

In the conduct and reporting of the various studies the faculty and research staffs of the laboratory all played important rules. In cooperation with the Director, the faculty and key members of the research staff served in an advisory capacity to all projects, sometimes with the counsel of special advisory groups selected from outside the University to aid in the technical guidance of individual studies. Each investigation was under the supervision of a member of the faculty serving as Faculty Investigator. Under him the work was carried out by a member of the research staff serving as Project Engineer and assisted by individuals assigned to the project, as well as by the technical staff of the laboratory, which provided the laboratory services to all investigations. Space does not permit a detailed listing of the individuals most directly concerned with each study reported. References cited in the foregoing paragraph, together with the staff listing, and the section on acknowledgments indicate in general who served most directly in conducting and reporting the various studies on which this report is based.

Acknowledgments

The Sanitary Engineering Research Laboratory is indebted to many agencies and individuals who contributed in a variety of ways to the progress of its investigations. Financial aid from California agencies, including the State Health Department, the State Water Pollution Control Board, and the State Water Resources Board; and from the Public Health Service and the Atomic Energy Commission made possible much of the experimental work. The advice and counsel of a great number of individuals was especially helpful. A partial listing includes Frank M. Stead, and E. A. Reinke, of the State Health Department; Dean C. Muckel, Leonard Schiff, E. A. Bliss, and C. E. Johnson, of the Soil Conservation Service; H.E. Hedger and Paul Baumann, of the Los Angeles County Flood Control District; Vinton W. Bacon, of the State Water Pollution Control Board; Harry Aggers, of the Union Oil Co.; Harvey O. Banks, of the State Water Resources Board; and Professor Paul R. Day, of the University of California. Former members of the S.E.R.L. staff who figured prominently in the investigations include Harvey F. Ludwig, now with the U.S. Public Health Service; Raymond V. Stone, Jr., A. E. Greenberg, and Carl H. Arness now with the California State Health Department; James A. Harder; Andrew K. Dinos; George E. Bell; Edwin W. Lee; Richard Hee; John M. Stewart; and others.

INTRODUCTION

Sources of Reclaimable Water

In a broad sense water reclamation might be considered as the treating or processing of any water to make it suitable for some useful purpose, most often for human consumption. Commonly, however, the term "reclamation" implies that the water concerned has been subjected to some prior use which has so degraded it in quality as to render it unfit for further useful purpose unless treated in some unusual manner. Typical of such a reclaimable water is domestic sewage and industrial wastes which derive from the vast quantities of water imported into our urban centers only to be wasted to the ocean after they have acquired what is in reality a quite minute burden of organic or other objectionable matter. It is a curious thing indeed that once a highly treated water becomes a vehicle for the transportation of human wastes, it is so identified with the material transported that it is no longer thought of as water. It is "sewage", or "domestic and industrial wastes", and as such is worthy of public rejection. If sewage creates a nuisance or menaces the public health it is given a rather thorough treatment in a special treatment plant, but it emerges still unidentified as water. It remains a "waste" and as such it is in fact too often wasted. Fortunately domestic and industrial wastes waters may lose their identity after being discharged to a stream and hence later become acceptable as usable water. Probably most of the water on earth has at some time been in contact with undesirable pollutants.

The circumstances involved in the water conveyance of wastes, especially from coastal cities, is without parallel in the history of transportation. In no other case is the transporting vehicle thrown away at the end of a single journey, and no other vehicle perhaps carries so light a load. In a typical domestic sewage, for example, some 2000 tons of water are sent forth to carry a single ton of solids. But because of the past association and the nature of this ton of solids, many engineers have talked as seriously of reclaiming sea water as of reclaiming sewage, in spite of the more than 60 tons of soluble solids dissolved in 2000 tons of sea water.

Clearly, domestic sewage and industrial wastes represent one very important source of reclaimable water; just how important may be judged from the example of the city of Los Angeles which discharges to the ocean from its Hyperion sewage treatment plant more than 250 million gallons of effluent each day.

A second major source of reclaimable water is flood water, representing surface runoff in excess of that which can be utilized immediately or impounded behind existing dams for future regulated use. Flood waters carry various amounts of suspended solids, mostly silts and other inorganic constituents of soil, which do not pose aesthetic or health problems as do the solids in sewage. The principal technical problems of reclamation of such waters, therefore, stem from the fact that they are seasonal in occurrence and produce large quantities of water during short periods of time. Quantity and natural quality together make flood flows an important source of reclaimable water.

Other reclaimable waters include cooling waters pumped from the ground, and such industrial process waters as can be kept separate from economically unreclaimable liquid wastes through process changes or through modified disposal procedures.

The virtually unlimited quantity of water in the ocean is alone sufficient to challenge the imagination of those concerned with the search for new sources of water supply. While the ocean must be seriously considered as an ultimate source of reclaimable water, the tremendously complicated problems of cost, power requirements, and technology support the conclusion that sea water is likely to be the last to be reclaimed for man's domestic and agricultural use unless great amounts of cheap energy should become available and much greater efficiency for salt removal can be developed. Brackish waters in coastal areas and saline ground waters, especially in the southwest, however, are more immediately hopeful as sources of reclaimable water.

Methods of Reclaiming Water

A number of methods of water reclamation are in use to a limited extent, under extensive investigation, or being considered as possibilities. Success of any of these methods depends for the most part upon technical and economic considerations which derive from the characteristics of the water to be reclaimed. In some cases public health considerations are also involved. In many cases the methods are still relatively unsatisfactory, both in technical refinement and economic development. In a few instances new methods of pre-treatment of waste waters offer the prospect of economic reclamation of the final effluent. An example of this possibility is the growing of algae on sewage and other organic wastes to produce a valuable material which when harvested leaves a water highly suitable for further reclamation.

It is important to note that in the reclamation of sewage and industrial wastes by any proposed method, the conventional treatment plant appears in an unaccustomed light — that of a device for partially reclaiming water rather than an expensive installation for conditioning a waste so that it can be wasted without complaints from health authorities. In some instances of industrial water, waste treatment plants alone may accomplish water reclamation on a scale large enough to have some importance in the total problem of a community's water supply.

One of the most economical reclamation procedures, applicable to domestic sewage and certain industrial wastes on a large scale, is the discharge under favorable conditions of suitably treated effluents into a stream capable of reclaiming them through dilution and through the natural self-purifying ability of flowing water. Under these circumstances the water is rendered suitable for useful purposes such as domestic supply, irrigation, aquatic life, and recreation. While the method in fact represents purposeful water management, it developed as a device for water reclamation through measures enforced by water pollution control agencies rather than as an engineered attempt to reclaim water. Consequently the discharge of treated wastes into a stream for the purpose of water reclamation must be carefully distinguished from situations in which inadequately controlled pollution exists but has not yet reached stream destroying proportions; and from situations in which the discharge of waste waters so pollutes a stream that not only the original pollutant but also the receiving stream must thereafter be wasted to the ocean unless some other method of water reclamation is applied to the mixture.

In California the reclamation of water by a combination of the waste treatment plant and the ability of surface streams to purify themselves is important but not to the degree observed in many other states, largely because of the intensive utilization of surface waters in the state. Presumably the method will continue in importance as California's population increases, although it may be expected that the sewage treatment plant will have to carry an increasing share of the total reclamation accomplished by the method. The method is somewhat applicable to flood water reclamation under circumstances where impounded flood waters are later released to a stream in regulated quantities, but in general this procedure is not looked upon as a reclamation technique in the sense that the term is used in this report.

The water reclamation method currently attracting widest interest through both field and pilot scale investigations, and through a few practical operations, is ground water recharge. Effluents from plants treating sewage and industrial wastes; excess flood waters, with or without treatment; and other reclaimable waters are discharged into the ground water either by application to the surface or by pumping underground. Surface application methods include spreading in ponds located on suitable pervious soil, over-irrigation of crops, and simulated rainfall. In each case the applied liquid is intended to enter the soil by infiltration and to percolate downward to reach the ground water table. Methods of pumping underground includes both direct injection into an aquifer and pressure pumping into a dry well. The most successful ground water recharge operations in the United States make use of direct recharge. Cooling waters and high quality industrial water pumped back into wells in the area which produced them are the best known examples. The method has several possible merits and an equal number of technical and economic uncertainties. These are discussed in greater detail later in this report.

The advantages envisioned for ground water recharge are that underground supplies may be replenished in the vicinity of cities where overdraft for water supply is severe; the process may in many cases be carried out on irrigated crop land with a maximum of benefits; advantage is taken of the filtering effect of soils and of the transporting facilities of aquifers; loss of producing aquifers to intruding sea water can be reduced significantly, and the loss of fresh water to the ocean reduced to a practical minimum; and evaporation losses from stored water are small when storage is underground. Furthermore, through storing water underground the vulnerability of water supplies to contamination by radioactive material in time of war would seem to be greatly lessened. When applied to flood waters the process might replenish the ground water basins currently overpumped for irrigation purpose, as well as those now used for public water supply. Recharge at proper points could reduce importation costs through making use of natural gravity distribution underground. Widespread application of ground water recharge to flood waters, however, is generally considered in connection with a program of flood control by dams and reservoirs.

Proposals to reclaim the waters of the oceans, or its tidal estuaries and bays or saline ground waters, have not, of course, involved ground water recharge either with or without pre-treatment in some type of plant. Dilution of partially reclaimed saline water either in surface streams or in ground waters where ion exchange is not a serious factor has likewise been but a small consideration. Most experimental work has been done on distillation by direct heating, by low pressure vacuum, or by solar energy; with ion exchange columns; and by means of perm-selective membranes which serve as ion traps. Some of these methods have been in use for a long time for small water supplies, principally for military installations, but their application to the reclamation of saline waters for public use or for irrigation has not yet reached the practical stage.

Inhibiting Factors

In any consideration of reclamation of waste, flood, saline, and other waters, and of the methods by which reclamation can be accomplished economically, it is well to note the factors which may tend to place limitations on the practice. Leaving technical and scientific problems for discussion in a later section of the report, it is still possible to outline certain trends and conditions which may be inhibiting. The per capita demand for water is increasing at a greater rate than population in much of the United States. This fact together with the rapid increase in population can only mean in California that even greater use will have to be made of existing surface waters - greater withdrawals for exportation to cities and agricultural enterprise, increased recreational use, and better engineering control. Inevitably streams will be less able to reclaim wastes by natural processes and, ultimately, will be entirely unavailable as devices for transporting wastes unsuitable for reclamation. Thus greater reliance wil have to be placed upon the reclamation ability of waste treatment plants.

In the case of industrial wastes, certain toxic and dangerous chemicals can make them unacceptable for reclamation by dilution or by ground water recharge. The presence of such materials in sewage may, therefore, limit the amount of water available for reclamation unless segregation of wastes within the industrial plant is practiced to an increased degree.

Somewhat more speculative is the effect of radioisotopes on water reclamation practice if industrial use of such materials becomes widespread, or if atomic power plants become commonplace. Some answers to the problems in water reclamation which might be imposed by radioactive materials will undoubtedly result from current investigations of the fate of radioisotopes in sewage and in the soil. Obviously the beneficial effects of nuclear physics may not be denied mankind, but equally obvious is the fact that the use of radioisotopes cannot be accompanied by the type of waste disposal practice to which Americans are accustomed.

GROUND WATER RECHARGE

General Problems of Ground Water Recharge

Ground water is the result of infiltration and percolation of water in the soil. Aquifers which are not overlain by impervious strata are directly recharged by precipitation striking the soil as raindrops, running over it in sheets when rainfall is intense and when the snow melts, or standing in surface puddles and ponds. Water enters the soil by infiltration and percolates downward with little lateral dispersion until it reaches a limiting zone of relatively impervious material. If this natural recharge occurs at an annual rate exceeding the rate of loss by outflow through surface or submarine outcropping of the aquifer and by withdrawal through pumping, a ground water reservoir is built up in which the water table continues to rise until equilibrium conditions exist between inflow and outflow.

Aquifers overlain by impervious strata are subject to natural recharge only at the outcrop of the aquifer or below the terminus of the impervious overburden. Most commonly such natural recharge is envisioned as taking place at the higher altitudes of the aquifer. Natural recharge, however, also occurs where an aquifer outcrops near a stream, especially during high water, and there are numerous instances in the western United States where streams diminish in flow as they progress across pervious soil. Recharge of aquifers may also result from contact underground with fissured stone into which water has flowed from streams or directly from rainfall. To some degree this may amount to direct pressure recharge.

The obvious fact that all ground water is the result of natural recharge through infiltration and percolation; through surface spreading; or to a lesser extent, through direct recharge, makes it as once evident that engineered recharge is possible. For reasons of economy, however, engineered water reclamation requires intensive recharge over relatively small areas. Hence ways are sought to increase the rate of infiltration or recharge to values far in excess of those encountered in nature. Spreading ponds or the flooding of spreading grounds located on especially suitable soil are the most common methods of induced infiltration, while injection of water under pressure is the most common method of direct aquifer recharge. Such methods are most conservative of water and require less extensive installations and surface area than simulated rainfall. Furthermore simulated rainfall returns too large a percentage of water to the atmosphere instead of to underground reservoirs.

The problem of ground water replenishment by engineering procedures is further complicated by the nature of the water available for salvage. As previously noted, reclaimable waters occurring in important quantities are essentially flood waters, domestic sewage, and industrial wastes. Flood waters invariably contain suspended matter which even under the most favorable conditions has a mechanical clogging, or surface sealing, effect on the soil or aquifer. Sewage likewise contains material in suspension, but the organic nature of this material adds biological phenomena to its ability mechanically to clog soils. However biological and organic materials may also aid percolation in some soils. In addition it contains matter inimical to the public health should its successful recharge into an aquifer result in contamination of ground waters. The same is true of industrial wastes which in many cases carry in addition to suspended matter or organic and inorganic nature, dissolved chemicals that may render ground waters toxic, or unpotable for aesthetic reasons such as taste and odor. All of these waters available for salvage, and especially industrial waste waters, are likely to contain some chemicals which may produce soil clogging through ion exchange - a phenomenon that is not characteristic of rain waters involved in natural recharge.

The engineering problems of ground water recharge center around questions other than the feasibility of ground water recharge. Rather, because of the nature of the reclaimable water available for artificial recharge, they concern such matters as:

1. The degree of pretreatment necessary to make acceptably high rate recharge possible.
2. The physical, chemical, and biological phenomena which bear upon the rates of infiltration, percolation, and recharge and which, consequently, determine the success or failure of any recharge enterprise.
3. The operational procedures necessary to maintain the ability of a soil or of an aquifer to accept recharge water.
4. The nature, maintenance, and operation of

ponds, infiltration wells, recharge wells, and other devices by which water to be reclaimed is applied to the geological strata.

5. The extent of movement of bacteria and chemicals, which affect water quality from a public health viewpoint, with water percolating through soil or with ground water.
6. The geological, environmental, and other conditions which govern the method of recharge to be used, i.e., surface spreading, over-irrigation of agricultural soils, and direct injection.
7. The economic considerations, both short range and long range, imposed on artificial recharge undertakings by the best obtainable answers to the foregoing groups of problems.

In addition to engineering problems, there is a variety of legal considerations involved in an extensive reclamation of water by ground water recharge. Excluding countless political involvements resulting from the conflicting interests, viewpoints, and motives in human affairs, there remains a difficult question answerable only by legislative action based upon a public policy acceptable to citizens. It concerns, for example, the ownership of recharged water: Who shall pay for recharge? What restrictions shall be placed upon its appropriation and use by public or private interest either through existing or future wells? What is a just arrangement with agricultural enterprise that benefits from use of water in a project of over-irrigation which also augments the ground water supply available for use elsewhere?

For purpose of this report it is assumed that legal considerations are not unsurmountable. Consideration is therefore confined to the general progress that has been made toward a solution to the engineering problems.

I. RECHARGE BY SPREADING

Development and Status of Ground Water Recharge by Spreading

Artificial recharge of ground water basins has been practiced in the United States for more than half a century. References are found in the literature to surface spreading of water in Orange County, California in 1896 (13) and in Denver, Colorado, in 1898 (14). Since that time the spreading of flood waters and other fresh waters has continued to attract the attention of civil engineers.

A 500 acre spreading ground was put in operation in 1916 at the mouth of San Gabriel Canyon (15) and has been in continuous operation since that time. In the early 1930's a test (13) was conducted in the San Fernando Valley in which Owens River water was successfully spread at appreciable rates for a two year period. At about that same time the Los Angeles Flood Control District began the development of extensive spreading grounds (14) for storm waters, of which the 443-acre Rio Hondo is the best known. At present more than 1800 acres of spreading grounds are operated by the District.

Surface spreading of sewage plant effluents to effect ground water recharge is a more recent development, one of the first planned studies being reported by Goudey (16) at Los Angeles in 1930. Goudey's studies demonstrated that a highly treated sewage could safely be applied to the ground water by spreading. Nevertheless the method was not widely adopted and in 1942 a Committee of the American Society of Civil Engineers found that planned waste water reclamation programs by ground water recharge were both rare and uneconomical.

In 1949, however, the case for waste water reclamation was clearly set forth by Arnold, Hedger, and Rawn (17) who found ground water recharge with treated sewage and industrial wastes to be both economically and technically feasible, and made specific recommendations for its adoption in the Los Angeles area. A plan was set forth by which some 125 million gallons of water could be reclaimed each day in a total of eight spreading operations. Experimental spreading basins were set up at Whittier and Azusa to demonstrate further the feasibility of sewage reclamation. During the same year, Freeman (18) recommended spreading a well treated effluent in the Oxnard area.

For a number of reasons, including unknown public health factors, and, perhaps, the tendency of humans to continue familiar practices, the Los Angeles County proposals were not put into practice on an important scale. However, an interest was aroused which led to further investigations and which seems certain to bring about ground water recharge with sewage and industrial waste effluents in California. In 1951 more than 70 smaller municipalities and sanitary districts were spreading sewage plant effluents for crop irrigation (12). In 1954, a total of 74 municipalities and sanitary districts, and 32 private and public institutions were reported (18) to be utilizing sewage plant effluents for irrigation. Use of such effluents for ground water recharge, unreported in 1951, was reported (19) as being practiced in 1954 by some 78 communities and 36 public and private institutions. Although but a few of these latter totals were using well engineered spreading basins, nearly all were depending on some sort of surface application other than crop or pasture over-irrigation.

Some idea of the national interest in ground water recharge may be obtained from the 1952 report (29) of Task Group E-4B of the American Water Works Association. Although the principal interest in ground water recharge was evidenced in California and the eastern seaboard, some types of recharge projects were under way in about 30 states. No breakdown was presented in the report to show the relative number of these projects concerned with surface spreading and with direct recharge, nor of the comparative numbers concerned with fresh water and with waste waters. A survey (19) prepared by the University of California at Los Angeles reported that there were 219 recharge operations in 32 states of the United States in 1953. Again no breakdown is available as to method of recharge of nature of water involved.

The successful flood water recharge experience in southern California as well as the proposed sewage spreading projects (17) and the original experiments at Azusa involved the use of quite coarse water deposited gravels and sands into which the natural rate of filtration or recharge is comparatively high. Many of the aquifers in California which are subject to serious overdraft, however, are overlain by much tighter soils, the most pervious of which range from fine sand to sandy loams. Studies of water spreading on a fine textured soil were started in

1936 in Kern County near Bakersfield and continued in 1944 by the Soil Conservation Service in cooperation with a number of other public agencies (21) (22) (23) (24) (25). From this project, which is still engaged in important water spreading tests, has come what are probably the most significant contributions to an understanding of the phenomena of infiltration and percolation, as well as the development of operational procedures for obtaining maximum infiltration rates. A similar study of spreading of sewage treatment plant effluents on fine soil was conducted at Lodi, California (10) in 1950-53 for the purpose of exploring the public health aspects of ground water recharge by sewage spreading, as well as the rates of infiltration, and the operational procedures required. These studies showed that recharge with water or highly treated sewage plant effluents is possible by surface spreading, albeit at modest rates of infiltration and percolation.

Some recharge rates for water, and for sewage plant effluents spread for purpose of ground water recharge are shown in Table I. Values are taken from various references, and from other sources, some of which provide incomplete data. Essentially the southern California water spreading grounds are debris cones or other water deposited coarse material. The Kern County (Bakersfield) soil is a Hesperia sandy loam and the Lodi soil on which sewage was spread is a Hanford fine sandy loam.

Experimental Studies of Spreading

Experience in engineered reclamation of waste water by surface spreading, while demonstrating the feasibility of such a procedure under favorable conditions, has produced but little knowledge of the basic phenomena which govern the rate at which a liquid infiltrates into a pervious soil, or which control its rate of percolation downward to the water table. Until quite recently, this was especially true of waters carrying solid matter in suspension, as well as of waters containing dissolved organic matter of a biochemically unstable nature. The result has been a serious limitation on the ability of engineers to judge the capacity of a soil to accept applied water, or to predict the probable degree of treatment of waste water necessary prior to spreading, without resorting to expensive and often time consuming field experiments. From many years of engineering experience with sand filters in water treatment it was evident that the surface of a medium filtering turbid water would soon become clogged, and although there are important differences between the phenomena of filtration and percolation it was obvious that a soil would likewise lose its ability to admit water. Nevertheless, there has been little in either spreading or filtration experience to indicate the operational procedures best suited to the maintenance of infiltration rates, nor to define the problems to be solved in the interest of engineered water reclamation by spreading. This

TABLE I

Some Observed Infiltration Rates in Water and Sewage Spreading

Locality*	Material Spread	Infiltration Rate acre/ft acre/day	Reference No.	Remarks
Tumunga Wash	Water	6	(26)	
Saticoy Spreading Grounds	''	2.8	''	
Canyon Basin, Azusa	''	1.2 to 9.3	''	
Anaheim Plot	''	0.75 to 3.1	''	
Lower Santa Ana River	''	3	''	
Lytle Creek	''	0.8 to 11.4	''	
East Orange, N. J.	''	0.4 to 0.5	''	
Perth Amboy, N. J.	''	2.3	''	
San Gabriel Canyon	''	0.5±	(15)	
Rio Hondo	''	1.6 to 3.5	(15)	
San Fernando Valley	''	3 to 10	(13)	
Santa Clara Valley	''	1.5 to 7	(27)	
Kern County	''	3 to 16	(22)	under various surface treatments
'' ''	''	1.5 to 2	(23)	
'' ''	''	4 to 5	(21)	
Los Angeles	Sewage Eff.	0.6	(16)	
Lodi	'' ''	0.5	(10)	
Lodi	Settled Sewage	0.15±	(10)	
Azusa	Sewage Eff.	1.2	(28)	
Whittier	'' ''	0.5 to 1.5	(17)	

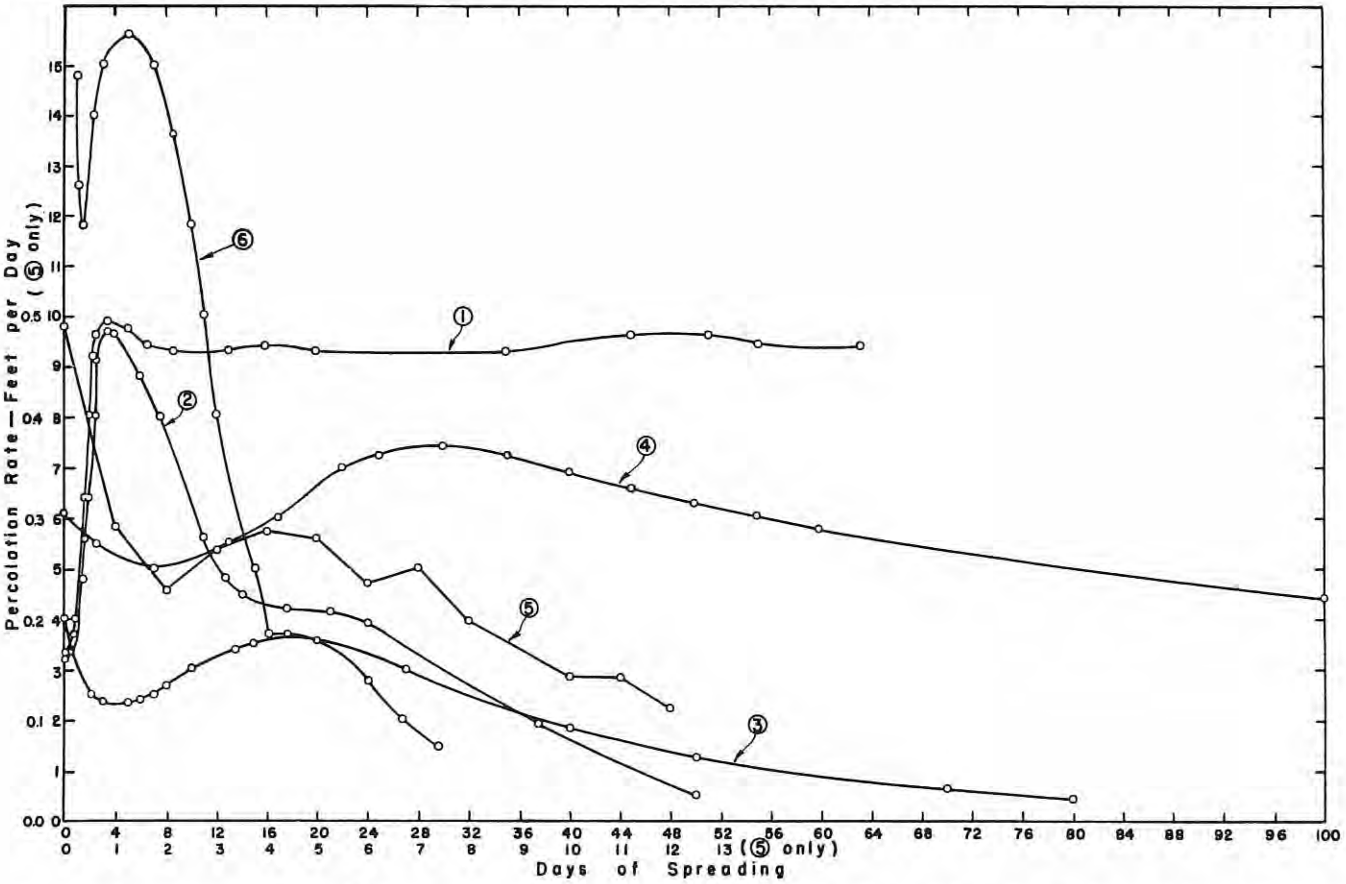
*California locality unless otherwise noted.

situation, together with a growing need for water in the southwest, led to a series of continuing investigations aimed at extending the fundamental knowledge of infiltration and percolation phenomena so that waste waters might be safely returned to the ground water through a variety of soils with a degree of success similar to that achieved by the Los Angeles Flood District with flood waters in alluvial deposits.

Infiltration Curves. The manner in which infiltration rates vary has been established by a number of recent investigations. In 1944 Christiansen and Magistad (29) reported the frequent recurrence of a characteristic time-rate curve in studies of infiltration of water into undisturbed soil plots and into core samples. This curve showed that infiltration rates were initially high but decreased rapidly to some minimum value. Thereafter, the rate curve rose quickly to a maximum which in some cases exceeded the initial rate of infiltration, then declined along a typical compound interest die-away curve to approach some steady state minimum. The investigations attributed the initial decrease in infiltration rates to structural changes in the soil due to swelling and dispersion of dry soil upon wetting, and to dispersion of clay particles by ion exchange between soil and percolating liquid. This possibility is borne out by previous studies by Bodman (30) and by others who showed that ion exchange has important effects on percolation rates.

The subsequent rise in infiltration rates was attributed to the dissolution of gases entrapped in the soil voids, while the final decline was associated with the continued action of bacteria producing biological growth products which clogged the soil voids. This theory of microbial clogging was later supported by Allison (31), who demonstrated that the final decline did not occur in sterile soil columns, but reappeared when such columns were reinoculated with bacteria.

In extensive studies of water spreading in the vicinity of Bakersfield, California for the purpose of determining the causes of infiltration rate decrease under prolonged submergence of soil, as well as for exploring methods for increasing and maintaining infiltration rates, Bliss, Johnson and Schiff (22) observed under a variety of conditions the same phenomena reported by Christiansen and Magistad, and by Allison.



1 Sterile soil and water (31)
2 Sterile soil, reinoculated (31)
3 Bakersfield Test Plot
4 Bakersfield Test Plot, Surface treated (24)
5 Lodi Test Plot (10)
6 Azusa Test Plot (19)

Fig. 1. Typical Time-Rate Infiltration Curves

Simultaneous with the Bakersfield studies other groups were observing the same type of infiltration curves when sewage plant effluents were applied to soil in spreading ponds. The Los Angeles County Flood Control District conducted field studies at Azusa (17) to determine among other things the organic loading which could be imposed upon spreading basins, and to obtain information on operational and maintenance procedures. At the same time the University of California was carrying on field investigations (10) at Lodi, California to obtain similar information for soils more typical than the coarse alluvium found at Azusa. In 1953 the Lodi Study was extended to other California soils by Orlob and Butler (6) using five typical pervious California soils in 3-foot diameter lysimeters. During the same period further observations were made at Azusa by Bush, Stone, et al (19).

All observers reported the occurrence of a typical S-shaped curve when either water or sewage was spread on undisturbed soil. The findings of several investigators under a variety of conditions on different soils are summarized in Figure 1. When the soil surface was disturbed by spading or plowing immediately prior to spreading, the recovery in infiltration rate which normally follows the initial decline rarely occurred. This is believed to result from dispersion of the surface soil particles by structural breakdown, rather than from entrapped air, becoming the limiting factor in infiltration rate. In this case essentially only the die-away portion of the rate curve remains, with rate decrease due to a combination of particle dispersion and pore clogging by slimes and gums which represent a part of the end products of microbial metabolism in the soil.

That these same products of biological growth can act to increase the rate of infiltration is shown graphically in Figure 2 which represents the rate of infiltration of primary

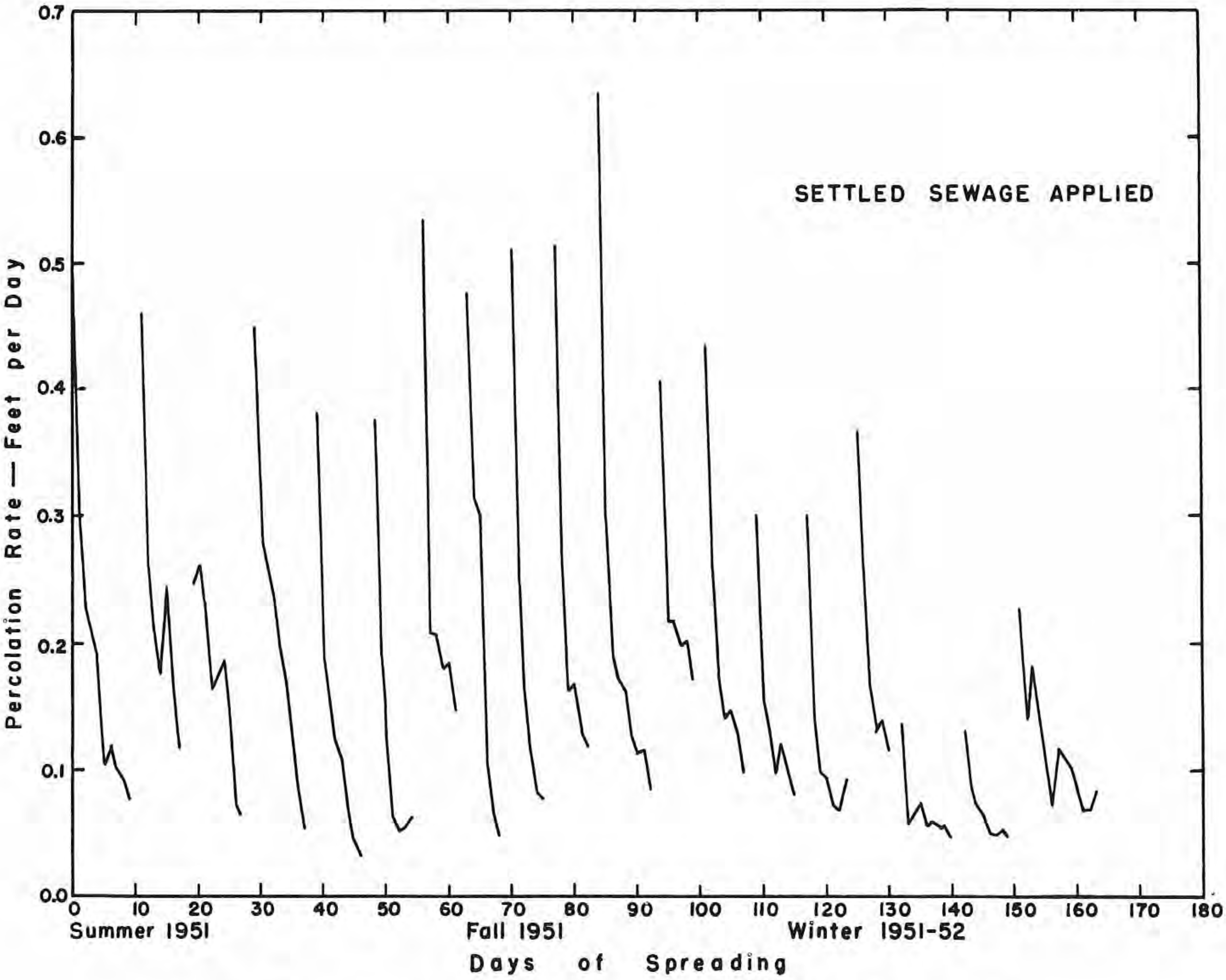


Fig. 2. Daily Percolation Rates For Spreading Basin At Lodi, California

settled sewage into the Hanford fine sandy loam soil at Lodi, California.

The spreading basin represented in Figure 2 was operated alternate one week periods of spreading and resting. The notable increase in infiltration rates after each period of resting is undoubtedly due to a change in the soil structure brought about by the aggregation of particles and biological activity during drying.

Infiltration Rates vs. Soil Particle Size. In order to generalize readily the results of experimental studies on particular soils as a basis for engineering judgment of other soils, it would be desirable to establish a simple correlation between some measurable physical characteristic of the soils and the infiltration rates which might be expected of them. The characteristic most commonly suggested is some function of particle size such as effective size, uniformity coefficient, and modal size. In situations where the chemical nature of the water to be reclaimed by spreading is not such as to disperse the clay fraction of the soil through ion exchange, this suggestion might seem to have greater merit than is borne out by experiment.

Table II presents the observed relationship between various measures of particle size in the surface zone of a number of soils and the observed rate of infiltration of sewage plant effluent after two or three weeks of spreading. The circumstances under which the various experiments reported were run are sufficiently similar for comparative purposes. One group of soils, as indicated in the table, were tested under identical conditions in lysimeter studies. The four Lodi test plots were operated under various conditions of treatment but the values given in Table II are for roughly similar conditions.

From the values reported in Table II it is evident that the comparative infiltration rates of two soils are not predictable from the relationship of the soil particle characteristics listed. While effective size and uniformity coefficient are generally reported for soils, they are of doubtful value because soil particle size distribution normally fails to follow a single logarithmic probability curve such as that observed for the sand fraction of the soil. The modal size has sometimes been suggested as a useful measure of comparative permeability, but again Table II fails to show a correlation between this measure and equilibrium infiltration rates. Numerous attempts have been made to formulate a relationship between some function of particle size and permeability but as yet there is no satisfactory device for estimating the field performance of a soil by a simple comparison of its characteristics with those of another soil for which field data on spreading are available. This means that observations of the individual soil on which it is proposed to spread water of any given quality are the most reliable basis for predicting its suitability for water reclamation by spreading.

Use of Lysimeters For Infiltration Tests. The cost of operating field test plots of the type used by the University of California at Lodi, where a number test basins 19 feet in diameter were used, or by the Soil Conservation Service in its Bakersfield studies, where a similar size of plot was constructed, is too great to recommend the method for preliminary engineering design and

TABLE II

Relation Between Soil Particle Sizes In Surface Stratum and Sewage Infiltration Rates As Reported From Various Tests

Soil	Eff. Size (mm)	Unif. Coeff.	Modal Size (mm)	Depth of Submergence (feet)	Equilibrium Infil. Rate (ft/day)
Azusa Plots (Alluvium)	0.40	68	40.0	1.0	1.2
*Hesperia Sandy Loam	0.002	67.3	0.180	1.0	0.5
*Hanford Fine Sandy Loam	0.0074	24.9	0.210	1.0	0.3
*Yolo Sandy Loam	0.021	8.1	0.170	1.0	0.3
*Oakley Sand	0.020	11.2	0.205	1.0	0.16
*Columbia Sandy Loam	0.0033	47.3	0.180	1.0	0.13
Whittier Plot (Sandy Loam)	0.044	4.3	0.22	0.5	0.6
(Hanford) Lodi Plot A	0.0032	67	0.6	0.5	0.58
(Hanford) Lodi Plot B	0.0035	86	0.25	0.5	0.25
(Hanford) Lodi Plot C	0.0032	67	0.6	0.5	0.58
(Hanford) Lodi Plot D	0.0018	78	0.25	0.5	0.17

*Under identical test conditions

cost considerations. In order to bring preliminary engineering costs of waste water reclamation into line with those of other engineering enterprises it is necessary that field tests be somewhat simpler than pilot test ponds. Having determined by test borings and other field observations that a pervious soil is not separated from the ground water by limiting strata, and having established the existing geographical and topographical relationships, the engineer then needs only reliable information on infiltration characteristics of the soil in order to estimate the feasibility of a proposed spreading operation.

One of the principal objectives of the lysimeter studies (6) conducted by the University of California was to determine the feasibility of using infiltration rates and other data obtained by spreading waste waters on soils in lysimeters to predict the behavior of those soils under field conditions. Soil lysimeters 3 feet in diameter and containing soil columns 3 feet in length were set up with Hanford fine sandy loam and Hesperia sandy loam. The field performance of the Hanford soil under spreading with fresh water, settled sewage, and sewage treatment plant final effluent was known as a result of the Lodi studies, while similar information had been obtained for the Hesperia soil under water spreading in the Bakersfield studies. In order to explore the further possibility of predicting the behavior of one soil type on the basis of that of another, three additional pervious soils were tested in the lysimeter studies. These were Yolo sandy loam, Columbia sandy loam, and Oakley sand. As indicated by the data in Table II, no basis for predicting the relative behavior of various soil types was established by the study.

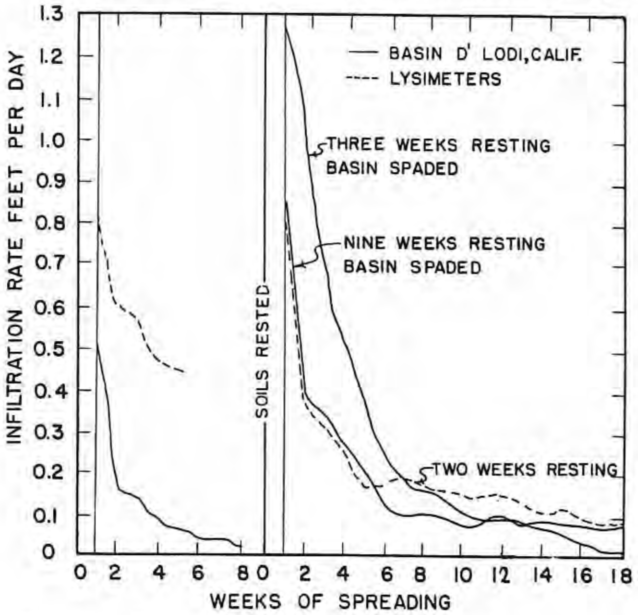


Fig. 3. Comparison Of Infiltration Rates For Hanford Fine Sandy Loam In Lysimeters And In Field Test Plots

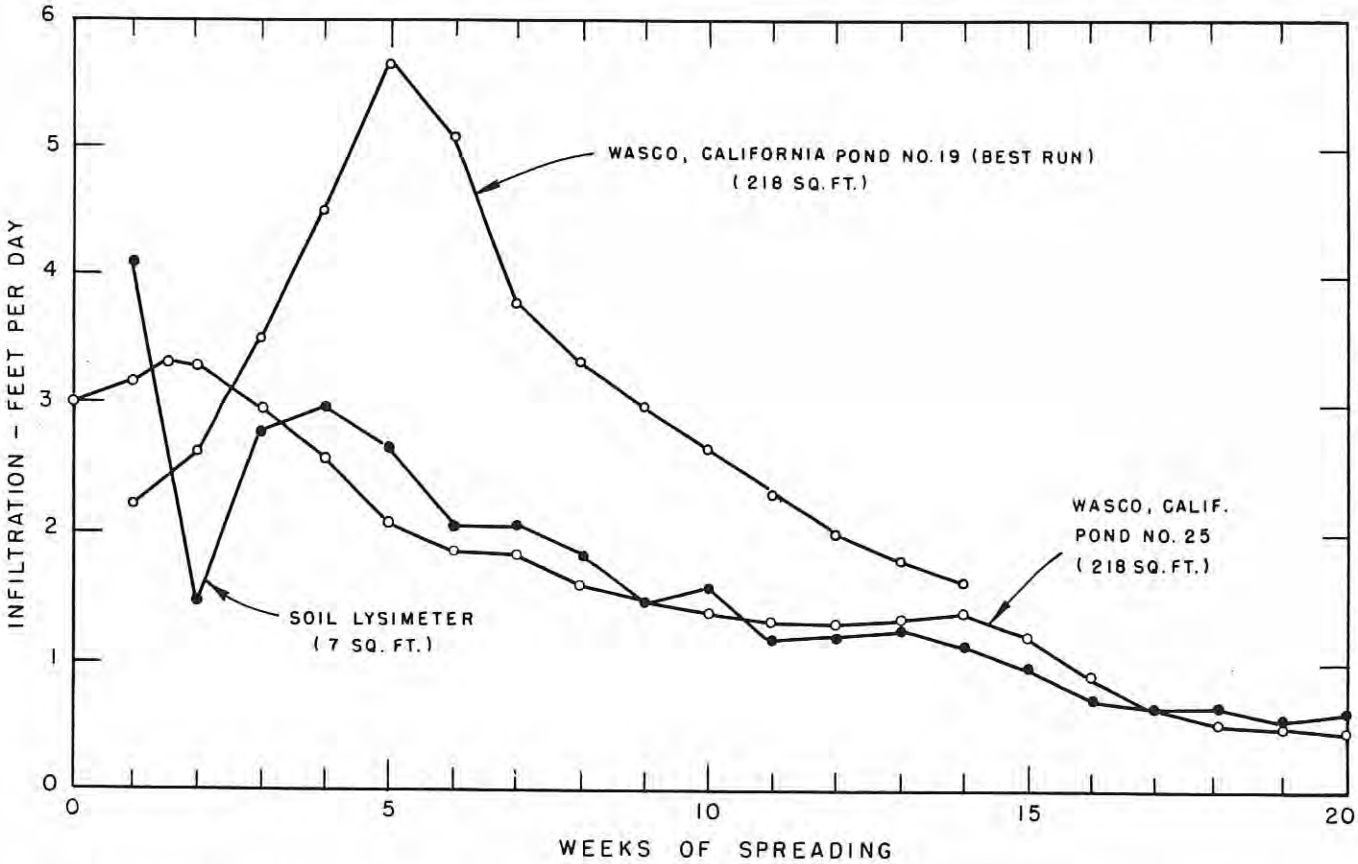


Fig. 4. Comparison Of Infiltration Rates For Hesperia Sandy Loam In Lysimeters And In Field Tests.

A comparison of rates of infiltration of settled sewage into the Hanford soil during similar periods for both lysimeters and a plot designated as Basin D' in the Lodi report (10) is presented in Figure 3 (on preceding page). Basin D', which produced higher infiltration and percolation rates than those obtained by any other operational procedure studied at Lodi, was subjected to periods of submergence, followed by drying and spading of the surface. Thus the soil was disturbed in a manner comparable to that used in operating the lysimeters containing Hanford fine sandy loam obtained from the Lodi area. The sewage applied to both Basin D' and the lysimeters was treated by primary sedimentation only, and the depth of surface inundation was comparable during the studies summarized in Figure 3. It is evident from the figure that the lysimeter results might have been used to predict with reasonable accuracy the behavior of Hanford fine sandy loam under field conditions of spreading.

Figure 4 (on preceding page) shows the comparative results obtained by spreading water on Hesperia sandy loam during the lysimeter studies (6) and in the field test ponds operated by the Soil Conservation Service near Bakersfield, California (22).

The Hanford soil used in the lysimeter studies was obtained from the site of the field test, and test conditions were generally similar. A striking similarity may be noted in Figure 4 between lysimeter data and those for a typical field pond throughout a period of 20 weeks. While there is a great difference in filtration rates between the lysimeters and Pond No. 25, on the one hand, and the "best run" curve obtained from Pond No. 19 (Fig. 4), all curves seem to approach the same equilibrium infiltration rate after 14 or 15 weeks. On the basis of Figure 4 it seems evident that a lysimeter study could have been used to predict the field performance of Hesperia sandy loam under water spreading.

Schiff (23) has noted that in field ponds such as those used in the Bakersfield studies some degree of lateral flow occurs which leads to higher infiltration rates than might be expected when a large spreading pond is used in the same location. At both Lodi and Bakersfield this lateral dispersion of infiltrating water was minimized at the test ponds by a diked area which was kept flooded with water. Assuming that such a device failed to restrict lateral flow as rigidly as the metal wall of a lysimeter, the true rates of infiltration per unit area in the field pond should be slightly less than those reported. Thus lysimeter infiltration rates would be somewhat higher than field pond rates of the same apparent magnitude. The difference, however, should not be great enough to cause difficulties in translating lysimeter findings into practical field estimates.

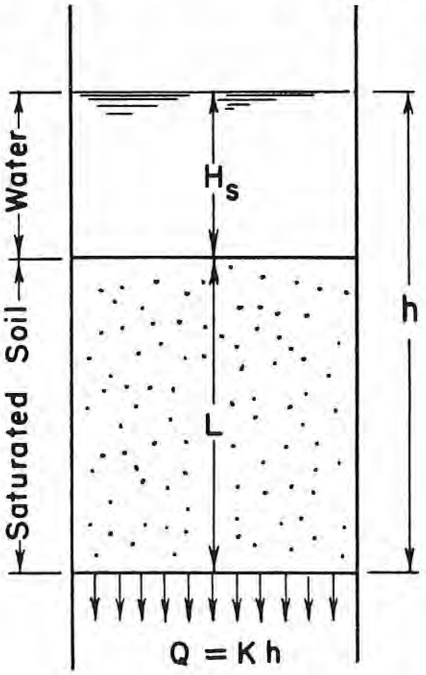
The most important objection to the use of lysimeters to predict field conditions has been the assumption that disturbed soil in a lysimeter will no longer have the characteristics it originally had in an undisturbed or field condition. Differences in packing, agglomeration of particles, and equilibria surely result from transferring a soil from its natural bed into lysimeters, but, contrary to expectations, the effect of this disturbance on infiltration rates under practical operating conditions is not profound, assuming of course that the soil in the field is not closely underlain by an impermeable stratum. This comes about by the manner in which pore space changes limit infiltration. Schiff (24), Greenberg (10), Orlob and Butler (6), and others have shown that clogging is a surface phenomenon which can be overcome by surface treatment of the soil. The evidence summarized in Figures 3 and 4 indicates that the surface in a lysimeter and in the field, rather than dissimilar lower strata, imposes the controls on infiltration rates.

In view of the foregoing experimental results it is concluded that when a pervious soil is not interspersed with less pervious limiting strata, lysimeter studies may be used to predict with reasonable accuracy the behavior of a soil under field spreading conditions, insofar as infiltration rates are concerned.

Infiltration Rate vs. Depth of Submergence. In order to minimize the cost of waste water reclamation by spreading it is important to limit land use to a practical minimum. Such a limitation depends upon the maintenance of high rates of infiltration, essentially through a combination of surface treatment of the soil and optimum depth of submergence. Both of these factors have been investigated to some extent, as noted in this and the following section of this report.

On the basis of general hydraulic considerations it might seem on superficial consideration that the rate of infiltration of water into a soil should increase directly with depth of surface inundation, at least until the soil becomes consolidated by the superimposed load of water sufficiently to impair its perviousness. Experiments, however, show that the relationship between surface head and infiltration rate is a complex one, depending both upon soil characteristics and the nature of the applied water. In a series of field pond tests with water spreading Schiff (23) found that an increase in surface head within a range of from 0.5 to 4.5 feet on a soil highly resistant to downward flow produced an increase in infiltration rates approximately proportional to the increase in depth of submergence, while in disturbed soils a change in surface head had little effect on infiltration rates. Orlob and Butler (6), working with disturbed fine California soils spread with water in lysimeters, generally verified this latter conclusion although they reported changes of significant magnitude when the surface head was varied from near zero to 2 feet. On the other hand, when sewage effluents were spread on a tight soil at Lodi (10) no appreciable change in infiltration rates was observed when the surface head was increased from 0.5 to 1.0 feet. Similarly Stone and Garber (28) reported that when sewage effluents were applied to fine soil at Whittier, California the maximum percolation rate could be varied but little, if at all, by increasing the surface head on the basin. They noted, however, that the infiltration rate in the coarse soil at Azusa (see Table II) could be increased during the initial stages of spreading by increasing the surface head.

While the foregoing reports may at first appear contradictory, sufficient evidence is available to show that they all support the same general conclusions concerning the relationship between depth of submergence, or surface head, and the rate of infiltration. In the work reported by Schiff, as well as in the lysimeter studies, it was shown that under conditions of so-called saturated flow in soils the familiar Darcy equation ($Q = kh$) may be applied to the flow of water. The hydraulic head (h) in the Darcy equation, however, consists of two parts as shown in the following diagram - the surface head (H_s), and the length of the saturated soil column (L).



The saturated soil column was found to be of short length in a soil of high resistance, thus the hydraulic head (h) was composed largely of surface head (H_s) and hence a doubling of this surface head approximately doubled the rate of infiltration, within the range of heads observed. An idea of the limited length of saturated soil column in a soil highly resistant to downward movement of water is indicated by the observation by Schiff that surface heads equal to those commonly used in water spreading were largely lost in the first 7-1/2 inches below the surface of undisturbed Hesperia sandy loam.

With disturbed soils the infiltration rates are generally comparatively high. The result is that the saturated soil column (L) is relatively long, hence the total hydraulic head is not greatly changed by what appears as large increases in the surface head (H_s). If, as is later shown to be the case, surface disturbance or other surface treatment materially improves infiltration rates, the matter of the effect of increased surface head under such conditions becomes of great importance to practical waste water reclamation by spreading. The actual benefits to be derived are limited, however, by the fact that surface treatment and increased surface head may only increase the infiltration rate up to the maximum ability of lower soil horizons to carry water. The combination is thus useful only when infiltration rates are governed by some surface zone which fails to admit water as rapidly as lower zones might accept it. Surface treatment alone is generally sufficient to care for this possibility, hence the prospect of high rate infiltration of water by use of deep ponds is not bright even though surface head is important in the operation of a water spreading area.

Experience with sewage spreading fails to show a proportional relationship between surface head and infiltration rate even though the length of saturated column is kept very small by the formation of a surface mat of organic matter. This is because sewage normally contains suspended matter which clogs the soil surface in proportion to the rate of infiltration. Thus any initial improvement in the infiltration rate following an increase in surface head is soon essentially lost by the greater clogging that accompanies the increase in infiltration rate. In the investigations at Lodi and at Whittier, Clogging apparently cancelled any benefits of increased surface head before they were observable.

In summarizing reported investigations it might be said that although experiments intended to establish the relationship between surface head or between hydraulic head and infiltration rates have by no means been exhaustive, enough has to be done to indicate quite clearly that:

1. In tight soils the rate of infiltration of water is approximately directly proportional to the surface head.

2. In disturbed soils the normal rate of infiltration under any depth of water can be improved by increased depth of submergence only in the case that, and to the extent that, lower soil horizons can carry water at a rate greater than the normal rate of infiltration.

3. The rate of surface clogging by suspended matter carried by sewage effluents is sufficient to mask effectively the benefits to infiltration rates of increased surface head.

From present experimental data it is evident that surface head is important in the operation of spreading areas for waste water reclamation. It also seems evident, however, that a modest depth of submergence should be adopted for preliminary engineering estimates with the expectation that while it may be modified in practical operation, such modification will not be great nor will spectacular changes in infiltration rates or land area requirements accrue from that modification. Depths of submergence of the order of 0.5, 1.0 or 1.5 feet might be used for estimating purposes with the expectation that they will not be greatly exceeded under practical operating conditions.

Effects of Surface Treatment and Operational Procedures on Infiltration Rates. A number of investigations of ground water recharge by surface spreading have yielded valuable information on methods for increasing and maintaining rates of infiltration into pervious soils. Table III presents a summary of findings from the operation of 8 spreading basins at Lodi, California.

A variety of surface treatments and operational procedures were reported (21) (22) (23) (24) as a result of the Bakersfield studies of water spreading conducted by the Soil Conservation Service. Chemical treatments included the application of gypsum and of calcium chloride for the purpose of altering water hardness, percentage of sodium in total salt content, etc. Surface conditioning included treatment with pumice, Ultra-wet, Krilium, Orzan, Flotal, and organic matter such as cotton gin waste, alfalfa

TABLE III

Summary of Relation of Infiltration Rates to Surface Treatment and Operational Procedures at Lodi, Calif.

Basin	Liquid Spread	Period of Observation Weeks	Operating Cycle		Surface Treatment	Weekly Av. Infiltration Rate ft/day
			Spreading Period-Days	Resting Period-days		
A	Final Effluent	32	7	7	Weeds growing in basin	0.254
A	" "	21	14	7	" " " "	0.305
A	Primary "	10	14	7	Weeds partially dead but not removed	0.114
B	Final Effluent	24	7	7	None	0.153
B	" "	19	7	7	Spaded at end of each cycle	0.254
B	" "	20	14	7	None	0.222
B	Primary "	10	continuous	0	None	0.108
C	Final Effluent	19	continuous	0	None	0.126
C	" "	42	continuous	0	Spaded prior to start of spreading	0.576
D	Fresh Water	24	7	7	None	0.095
D	" "	18	7	7	Spaded at end of each cycle	0.168
D	" "	9	14	7	None	0.105
D	Final Effluent	20	14	7	None	0.109
A'	Primary Effluent	10	7	3	None	0.143
A'	" "	11	14	7	None	0.042
A'	" "	16	14	7	Spaded prior to start of spreading	0.186
B'	Primary Effluent	26	7	7	3" of sand spread on soil	0.170
B'	" "	4	7	7	Top 1" of sand replaced	0.060
B'	" "	3	14	7	Top 1" sand replaced	0.037
B'	" "	3	14	7	All sand removed	0.028
B'	" "	3	14	7	Krilium added, 1#/100 sq. ft.	0.045
B'	" "	5	continuous	0		0.055
C'	Primary Effluent	37	7	7	None	0.093
C'	Final Effluent	13	continuous	0	Spaded prior to start of spreading	*0.621
D'	Primary Effluent	8	continuous	0	None	*0.145
D'	" "	16	continuous	0	Spaded prior to start of spreading	*0.272
D'	" "	16	continuous	0	Spaded prior to start of spreading	*0.198

*Average rate showed tendency to decline from week to week.

TABLE IV

Summary of Effect of Various Surface Treatments and Operational Procedures on Infiltration Rates at Bakersfield, California

No.	Treatment	Effect on Infiltration Rates
1	Gypsum added (4 tons/acre)	Small temporary increase.
2	Gypsum added in 9 successive applications. Soil plowed.	40 percent increase during application of gypsum, followed by decline to original rate when application stopped.
3	Hardness of 200 ppm maintained with $CaCl_2$. Soil plowed.	Temporary increase.
4	Topsoil removed (2'')	Pronounced decrease.
5	Surface crust removed after period of spreading.	Little or no effect.
6	Surface Spaded.	Increase on Hesperia soil when spading followed long periods of flooding and drying. Decrease on Exeter soil.
7	Submerged soil surface raked daily to remove gas bubbles from microbial activity.	No increase.
8	Auger holes drilled into subsoil and filled with gravel.	Little effect except where sand strata intersected.
9	Cotton gin mill waste applied in 6'' layer, kept moist for 30 days incubation, then dried before spreading.	Large increase, 3 to 4 times previous rate. Effect long lasting.
10	Alfalfa hay spaded under, and pond dried for approx. 7 weeks.	Large increase. Several months required for subsequent decline to approach previous low rate.
11	Bermuda grass or Paragrass grown in spreading pond in very dense stand.	Increase almost as great as that resulting from use of cotton gin mill waste.
12	Ultra-wet added to water at rate of 50 #/acre.	No appreciable effect.
13	20% pumice (by vol.) added to top 3'' of soil.	Some increase in one test, very little effect in another.
14	0.1% Krilium #186 (by wt) added to top 3'' of soil.	Large increase over prolonged period.
15	0.5% Orzan (by wt) added to top 3'' of soil.	Considerable increase.
16	0.4% Flotal (by wt) added to top 3'' of soil.	Little increase.
17	Short periods of rest in which soil did not dry out.	Temporary decrease.
18	Short periods of rest in which soil dried somewhat.	Temporary decrease.
19	Long periods of rest in which top 6'' of soil well dried.	Original rate often recovered.

hay, and various grasses. Mechanical procedures such as topsoil stripping, spading, raking, drilling holes and backfilling with gravel were also investigated, as were such operational procedures as various lengths of alternate spreading and drying periods, depth of submergence, etc.

The principal treatments used in these studies, together with the resulting general conclusions relative to infiltration rates are summarized in Table IV (on preceding page). The reader is referred to the original publications cited for a detailed statement of the conditions of the tests and a complete discussion of the results and their implications.

A comparison of the average infiltration rates for Basins A and B in Table III, when spread with final effluent on a 7-day spreading and 7-day resting or drying period, indicates that growing vegetation has an appreciable effect in increasing sustained infiltration rates. Under otherwise identical conditions of operation, Basin A, with a luxurious growth of vegetation, averaged 0.254 feet of sewage infiltered per day for 16 weeks of spreading (32 weeks of observation), while Basin B, with an undisturbed bare surface, accounted for but 0.153 feet of sewage per day during 12 weeks of spreading. This increased infiltration rate in the presence of a growing cover is confirmed by the results of the more exhaustive studies of the effect of vegetation on water spreading carried out by the Soil Conservation Service, and summarized as Item 11 of Table IV.

Table III indicates also that spading of the surface of Basin B increased its ability to accept sewage by some 66 percent, while a similar treatment of Basin D increased its water infiltration capacity by approximately 77 percent. An even greater increase in sewage infiltration rates is shown by Basins C and A', in which the percentage increases due to spading were 256 and 343 percent, respectively. A less spectacular effect was observed (Item 6, Table IV) when the Hesperia soil was spaded during water spreading studies.

Because of the surface clogging ability of the suspended matter in sewage, spading might generally be expected to have a more pronounced effect on sewage spread soils than on soils spread with water, despite the fact that such was not the case with Basins B and D. Particle size characteristics and other factors enter into the behavior of different soil plots, hence the value of spading any individual spreading area may have to be determined by trial in the field. On a practical scale, the method of surface spading becomes an important consideration. Unless the soil is well dried before the spading operation begins there is every likelihood that the weight of equipment used in the process will lead to the formation of a "plow pan" or other impervious layer below the soil surface. It might be necessary to resort to special equipment should spading prove to be especially beneficial to the infiltration capacity of a particular spreading area.

Basins A, B, and D in Table III all showed increased infiltration capacities when the operating cycle was changed from equal periods of spreading and drying, to 14 days spreading followed by 7 days of drying. Basin A' failed to conform to this pattern, and B' may also have shown a reverse tendency, although the number of other variables involved in this case observe the effect of the operating cycle on already minute infiltration rates.

From the results observed at Lodi it is evident that infiltration rates are reduced when the amount of organic matter is increased. In all cases where the only change in operating conditions was a change from final effluent to primary effluent a decrease in average infiltration rate was observed. As previously noted, this is the result of a continuous buildup of fresh decomposable solids in a filter mat at the soil surface.

Various observers have found that the addition of organic matter to a soil will result in increased infiltration rates under proper conditions. Schiff et al have shown in studies with cotton gin mill wastes (Item 9, Table IV) that added organic matter serving as a substrate for bacteria hastens the decline of infiltration rates in the manner suggested by Allison (31). They discovered, however, that during a 30-day period of incubation the cotton gin mill waste and other organic materials investigated were stabilized to a great extent by bacterial action. The life processes of the bacterial population produced gels and other products which so altered the soil structure by shrinkage during a drying period that infiltration rates were thereafter greatly increased.

In the case of sewage, however, as observed at Lodi, the continuous addition of raw organic matter interferes with the period of incubation with the result that both drying and surface spading seem to be necessary to maximum infiltration rates. The Lodi studies showed that on Hanford soil spread with either final or primary sewage plant effluent, a preliminary spreading period followed by basin resting and spading produced infiltration rates higher than those obtained by any other method studied. A similar procedure, without spading, was found to be the most effective for water spreading on the Hesperia soil at Bakersfield.

Results of various attempts to alter the structure of soil at the surface are summarized in Tables III and IV. As shown in Table III (Basin B') the addition of three inches of sand to the surface of a spreading basin led to no important change in infiltration rates. Low rates of infiltration remained low, although variable, and eventually a limiting zone built up below the sand layer which continued to produce minimum infiltration rates after the sand had been removed.

The application of Krilium to the surface of Basin B' may have induced a small increase in the infiltration rate over that prevailing at the time the Krilium was added, but at best rates remained so low as to cast doubt upon the efficiency of the material. This experiment was not pursued and the value of Krilium remained unestablished at the close of the Lodi study. More comprehensive work was done on a small spreading pond at Bakersfield. As shown by Item 14 of Table IV, the result was an impressive increase in the infiltration rate over a significantly prolonged period of time. A later study on a half-acre plot was less spectacular in its results but there was evidence that conditions in that particular situation were such as to produce infiltration rates essentially equal to the percolation rate in lower horizons, without any altering of surface conditions. As noted in a previous section of this report, nothing can be gained by increasing infiltration rates beyond existing percolation rates.

In the lysimeter studies of Orlob and Butler further observations were made on the value of Krilium in improving infiltration rates. In this case the disturbed soils used exhibited percolation rates in excess of infiltration rates, inasmuch as sewage solids produced a limiting zone in the surface layer of the soils tested. Applications of Krilium "Loamaker" to the top 3 inches of Yolo and Oakley soils produced a significant increase in the permeability of their surface strata and led to increased infiltration rates for both water and sewage. Under water spreading the Yolo soil showed an increase in infiltration capacity with time and reached an equilibrium rate of some 10 feet of water per day. The three finer soils tested - Hanford, Hesperia, and Columbia - showed some increase in infiltration capacity under water spreading, but no benefit accrued when sewage was spread. The increased rate observed when sewage was applied to the coarser Yolo and Oakley soils disappeared entirely in 6 to 8 weeks. Examination of the soils indicated that organic matter had penetrated the looser surface structure created by the Krilium and eventually established a limiting zone at greater than normal depths below the soil surface.

There was no evidence in any of the studies that Krilium was subject to bacterial attack, hence it showed no tendency to hasten clogging in any case as did biochemically unstable organic matter. Results of experiments with other surface treating agents are shown in Table IV, but none approach the apparent benefits of the few most successful methods.

Investigations thus far reported indicate that in water spreading on tight soils in which the percolation rate exceeds the normal infiltration rate, surface treatments such as perennial grasses, Krilium, and organic matter well incubated and dried are effective in increasing infiltration rates. In the case of sewage spreading, intermittent periods of spreading and drying, combined with surface spading to help break up the limiting mat of organic matter, seem most conducive to highest infiltration rates. This means that in engineering planning of sewage reclamation by surface spreading consideration must be given to methods of surface cultivation which will not result in subsoil compaction.

Practical Infiltration Rates. As has been amply demonstrated in the vicinity of Los Angeles area, ground water recharge by surface spreading of surplus water can be carried out on particularly suitable soils at rates approaching 2 feet depth of water on the spreading area per day. Most of the pervious soils of California, however, are much more resistant to downward flow of water than are the alluviums of the San Gabriel and similar valleys. Consequently spreading operations must be predicated on much lower infiltration rates, especially when sewage or other waste waters containing organic matter are to be reclaimed.

Results with both primary and final sewage plant effluents at Lodi, California led to the conclusion that for best rates of infiltration a highly clarified water should be applied. Under the best operating conditions developed at Lodi it was found that the final effluent from a sewage treatment works could be recharged at a rate of about 0.5 feet depth of water per day into the Hanford fine sandy loam of the area under a surface head of 0.5 to 1.0 feet. A similar surface head produced an infiltration rate of slightly less than 1 foot of sewage plant effluent into the fine sandy loam at Whittier, California, while only about 1.2 feet per day could be sustained in the coarse alluvium at Azusa. Sustained rates of sewage infiltration into Oakley, Yolo, Columbia and Hesperia soils likewise ranged from 0.2 to 0.8 feet per day. The Hesperia soil at Bakersfield accepts from 1 to 4 feet per day under sustained spreading by optimum operating methods.

On the basis of present data it is concluded that in the absence of specific lysimeter or field data on a particular soil, preliminary estimates should be based upon from 0.5 to 1.0 foot of water, or 0.25 to 0.5 cfs per acre, per day.

II RECHARGE BY INJECTION

Development and Status of Ground Water Recharge by Injection

For obvious reasons of economy and convenience, attempts to recharge the ground water by surface spreading were begun much earlier and have been more numerous than similar work aimed at direct injection of water into underground formations. Nevertheless, serious consideration of recharging underground formations dates back some 25 years. There are several reasons why direct recharge might be preferable to surface spreading:

1. By concentrating the operation it reduces land area requirements, and hence some aspects of cost.

2. By eliminating surface ponds mosquito control is not required, possible odor nuisance from sewage effluents is eliminated, and general environmental considerations do not become limiting.

3. It can be used in many areas where surface spreading would be impractical due to the existence of impervious strata between pervious surface soils and ground water horizons.

4. Where a number of pervious strata underlie an area, the most suitable aquifer can be selected for recharge. This makes possible better economy of surface location of point of recharge.

5. Where a number of water horizons exist recharge of an appropriate stratum could be designed for the minimum resulting effect on ground water quality.

6. It is adaptable to waters of a quality unsuitable for surface spreading, such as oil field brines and industrial wastes the injection of which might have a secondary effect on ground water conservation. For example, recharge of low quality water might replace oil underground for the purpose of preventing surface subsidence and fracture which can cross connect usable ground water with low quality liquids.

7. It makes possible wider use of ground waters for cooling purposes, in that high grade water can be utilized economically for the low grade purpose of heat extraction, then returned underground in a condition for high grade consumptive purpose.

For reasons of necessity, much of the successful experience has been concerned with the last two items listed. The oil industry has been active in recharge operations because of its need for secondary oil recovery as well as for disposing of oil field brines; and other industries have become interested because of a great need for certain process waters in areas of local ground water shortages. As noted in a previous section of this report, overdrafts on ground waters to meet the agricultural, industrial, and domestic needs of growing populations in California and elsewhere in the southwest have more recently turned attention to the reclamation of flood waters whose burden of silt or organic solids impose added problems of recharge.

Clogging of Injection Wells. Little experience with recharge of water containing organic solids was reported prior to the experimental studies discussed in the following section of this report. The literature on the subject of direct injection is in general agreement that recharge water should be clarified in order to prevent aquifer clogging. Experiments conducted in Los Angeles and reported by Harrell (32) in 1935 led to the conclusion that recharge water must be clear and relatively free of bacteria or materials on which such organisms will grow, if clogging is to be prevented. Some ten years later Meinzer (33) also noted that clogging results both from suspended matter and bacterial growths and suggested that recharge water be as clear and sterile as practical. Laverty (34) noted that much difficulty has been encountered in attempting to recharge water of poor chemical and bacterial quality. More recently Brashears (35) and others have concluded that the recharging of deep aquifers is practical provided water is desilted. The oil industry, which has had the most successful experience in recharging deep aquifers, has found that clogging may result from jamming of the aquifer by attempting to recharge at too high a rate, as well as from sediments; and in the fine-grained material from which oil is often obtained quite small rates of injection may prove to be too high.

Some clogging has resulted from ion exchange in the soil. In the San Fernando Valley, Lane (36) reported that imported clear fresh water clogged recharge wells in coarse granitic alluvium after but short periods of operation. The conclusion reached was that rearrangement of soil particles by the recharging liquid tends to bring about soil clogging. Holbrook, Young, and Wilbur (37) found the average life of recharge wells in the Allegheny injection field in New York to be 12 to 15 years when water was injected into 1250-foot borings at well head pressures of from 500 to 1200 psi. In the Texas oil field, Heithecker (38) reported the clogging of two of six wells into which a total of 100,000 bbls of water per day were introduced, although the water was first treated to remove sand, clay, sticks, grass, and waste oil.

Clogging of wells due to the swelling of clay colloids in the aquifer was observed by Hughes and Pfister (39). Others have reported clogging due to iron. Alcorn (40) described clogging of a well recharged with oil brines by iron sulfide resulting from anaerobic bacterial action. Schmidt et al (41) reported a similar difficulty with iron oxide, and Rhea and Miller (42) found ferric hydroxide to be the clogging agent in wells 4000 feet deep penetrating 100 feet of injection sand in the Texas oil fields.

Plummers (43) reported that micro-organisms common in oil field waters cause precipitates of ferric hydroxide, sulfur, metallic sulfides, and calcium carbonate; and that gelatinous material, elutrious substances, and organic plant threads separately and collectively have strong clogging effects if occurring in injected water. In the wells reported by Rhea and Miller, caving of the injection sand occurred, and sulfate splitting organisms appeared in the injection section. It is conceivable that the presence of sulfate splitting organisms in organic materials underground might contribute to the clogging of aquifers recharged with sewage plant effluents, provided other factors did not first close the pores of the aquifer material.

The effect of suspended and dissolved organic matter in clogging recharge wells, as observed by the University of California at Berkeley (4), is reported in a following section of this report.

Rates of Ground Water Recharge. Most available information on rates at which ground water might be recharged by direct injection concerns experience with oil field brines or with clear water. Although recent experimental work has furnished some important data with waste water. Rates observed in oil field operations are generally lower than would seem practical in ground water recharge for reclamation purposes and involve very high injection pressures.

In the 1250-foot wells described by Holbrook (37), in which pressures ranged from 500 to 1200 psi, the rate of injection amounted to only 1 to 3 bbls per day per foot depth of sand having a porosity of 16 to 18 percent and a permeability of 3 to 10 millidarcys. Similar low rates with oil field brines are mentioned by Riggs and Smith (44), and by others (45) (46) (47) (48), who note that under 500 psi, rates of recharge of 1200-foot wells amounted to 0.6 gal/min/foot of sand. Rates as low as 0.15 to 0.45 gal/min/ft are reported by Cashell (49) and by Terrill (50). Cecil (51) describes the injection of gasoline plant wastes into a 300-foot well at rates of 0.8 to 1.3 gal/min/foot of sand.

Many experiments with fresh water have not been reassuring. The shallower wells necessarily involved in fresh water recharge make lower injection pressures imperative. In many cases this about offsets the effect of the greater porosity and permeability normally found in aquifers in comparison with oil-bearing sands. In the Los Angeles tests (32) one well was successfully recharged at 0.6 gal/min/ft of aquifer penetrated, while another took only about one quarter of that amount. Lane (36) notes that the San Fernando Valley studies which resulted in failure by clogging did so at rates of about 7 gal/min/foot even though the aquifer material was a coarse granitic alluvium. Injection of surface waters into aquifers at El Paso, Texas was described by Sundstrom and Hood (52) in 1950. Rates observed were not of important magnitude. More recent reports of a recharge project at El Paso, however, show rates of about 700 gpm in wells slightly less than 900 feet in depth. A similar report of continuing recharge tests at the King Ranch in Texas appear hopeful but shows difficulties with rates of 7.5 gal/min/ft of aquifer having a permeability coefficient of 270 gal/sq. ft./day.

The most extensive experience with ground water recharge has been in Long Island, where water drawn from wells is returned underground after use in air conditioning and other cooling devices. Johnson (53) reported in 1948 that recharge rates of 100 to 550 gpm were achieved in various of 221 wells, 44 of which are operated the year round. From the data presented it has been calculated by the authors of this report that the injection rates at Long Island vary from 6 to a little more than 8.5 gal/min/foot of aquifer. Values of this order under sustained operation, demonstrate that ground water recharge with fresh water is practical under favorable conditions. To be of importance in water short areas such as the southwest, however, the method must be capable of application to the reclamation of waste waters. As previously noted, such waters generally carry suspended and dissolved organic matter which is known to have a serious clogging effect in a recharge well.

Experimental Studies of Injection

Beyond demonstrating that suspended matter in a recharge water will result in well clogging, the somewhat meager fund of engineering experience in direct recharging of underground formations prior to 1949 contributed almost nothing to a knowledge of well operation for the purpose of reclaiming waste waters containing suspended and dissolved organic matter. In 1949, however, the then newly established California State Water Pollution Control Board began a program of defining the problems, and finding answers to important questions associated with the reclamation of waste waters in California. One of its most significant projects was a 44-month laboratory and field investigation (4) of direct water recharge into underground formations, carried out by the University of California at Berkeley, and completed in December 1954. Aside from a primary concern with the public health and water quality aspects of water reclamation, as discussed in a subsequent section of this report, the investigation was intended to explore:

1. The use of recharge wells as a means of waste water disposal and ground water replenishment.

2. Methods of operating and maintaining recharge wells at sustained optimum injection rates.

3. The economic aspects of ground water recharge through wells.

Other important investigations conducted during the same years included scale model studies of hydraulics of injection wells (5) and field studies of fresh water injection, conducted for the California State Division of Water Resourses by the University of California and the Los Angeles County Flood Control District, respectively. Although these studies had for their major purpose the control of sea water intrusion, they, nevertheless, produced important information on ground water recharge with fresh water.

Recharge Wells. Both ordinary drilled wells with casings perforated in the region of the aquifer, and gravel packed wells cased in the same manner were used in experimental field studies. In model studies, tests were conducted with wells perforated throughout the depth of the aquifer, near the top of the aquifer only, and near the bottom of the aquifer only. Twelve-inch diameter recharge wells were used in the Richmond studies of the University. They penetrate a shallow (3 to 5 foot) water deposited pressure aquifer interspersed with thin layers of less pervious material, and located some 95 feet below the ground surface. The average permeability of the aquifer, as determined from drawdown and recharge tests, is 1900 gallons per square foot per day. The effective size and uniformity coefficient of the aquifer as determined from 17 of 23 wells drilled for recharge and observation purposes average 0.56 mm and 6.9, respectively. Aquifer overburden consists of several heavy strata of clay with occasional thin strata or lenses of sand and gravel, two of which are water bearing. Water in the aquifer is normally under a piezometric pressure of about 80 feet.

Six 12-inch recharge wells are used by the Los Angeles County Flood Control District at Manhattan Beach. These wells pass through beach sand and clay into water bearing formations having a permeability of from 800 to 1500 gallons per square foot per day and of various thickness up to about 100 feet.

For laboratory studies a lucite model was used to confine 30-mesh quartz sand of an effective size of 0.22 mm and a uniformity coefficient of 1.3. Model injection wells were located along one side of the aquifer in order to make possible the observation of movement of the interface between injected and ground waters. Because scale factors necessarily used in model studies magnify the prototype well diameter, no attempt was made to use the model in studies of well clogging by suspended matter. Rather it was used to observe the movement of injected water in the aquifer.

Construction and other features of recharge wells used in the University of California experiments discussed in this report are shown in Figure 5 (on following page).

Recharge wells without gravel packing did not prove to be successful in field investigations. The ordinary type well first used in the Richmond studies (see Fig. 5) was developed at rates of from 40 to 100 gpm by pumping at various times for periods of a few hours, and finally by pumping at 70 gpm continuously for a period of 20 days during which the drawdown remained constant at 78 feet. During this period the well behaved in a manner common to successful new wells, yielding muddy water at first, then clearing up and remaining clear during an extended period of pumping. After approximately one year of successful recharge with fresh water at rates of 13.5 and 37 gpm, injection of a mixture of 90 percent water and 10 percent of primary settled sewage was begun. Within two months the well failed by breakthrough of recharged water to the ground surface. It was subsequently determined (4) that failure began within a month after the start of fresh water recharge at a time when the well was discharged at 400 gpm for 30 minutes and at 70 gpm for three days to relieve clogging produced by ion exchange with a sodium chloride tracer. Thereafter pressure reversals during short periods of pumping brought about a progressive fracture and fall-in of aquifer overburden.

The first recharge wells used by the Los Angeles County Flood Control District at Manhattan Beach failed in a manner similar to the Richmond well. These wells were originally developed at rates of from 400 to 900 gpm for periods up to 16 hours, then recharged with fresh water at a rate of 400 to 900 gpm. The first well failed in about one month by subsidence of a considerable area adjacent to the well, forming a sink some 15 cubic yards in volume. Subsequently 2 more wells likewise caved in. Attempts to repair wells by gravel packing were only partially satisfactory since only one well was recovered for further recharge. At Richmond both gravel packing and grouting of the fractured overburden were carried out but the results were not sufficiently successful to re-establish the suitability of the well for recharge experiments. As a result of their experiments, The Los Angeles County Flood Control District has strongly recommended that recharge wells should be gravel packed.

The gravel packed well used in the Richmond experiments and constructed as shown in Figure 5 proved satisfactory. Sewage effluents of various concentrations were injected through this well

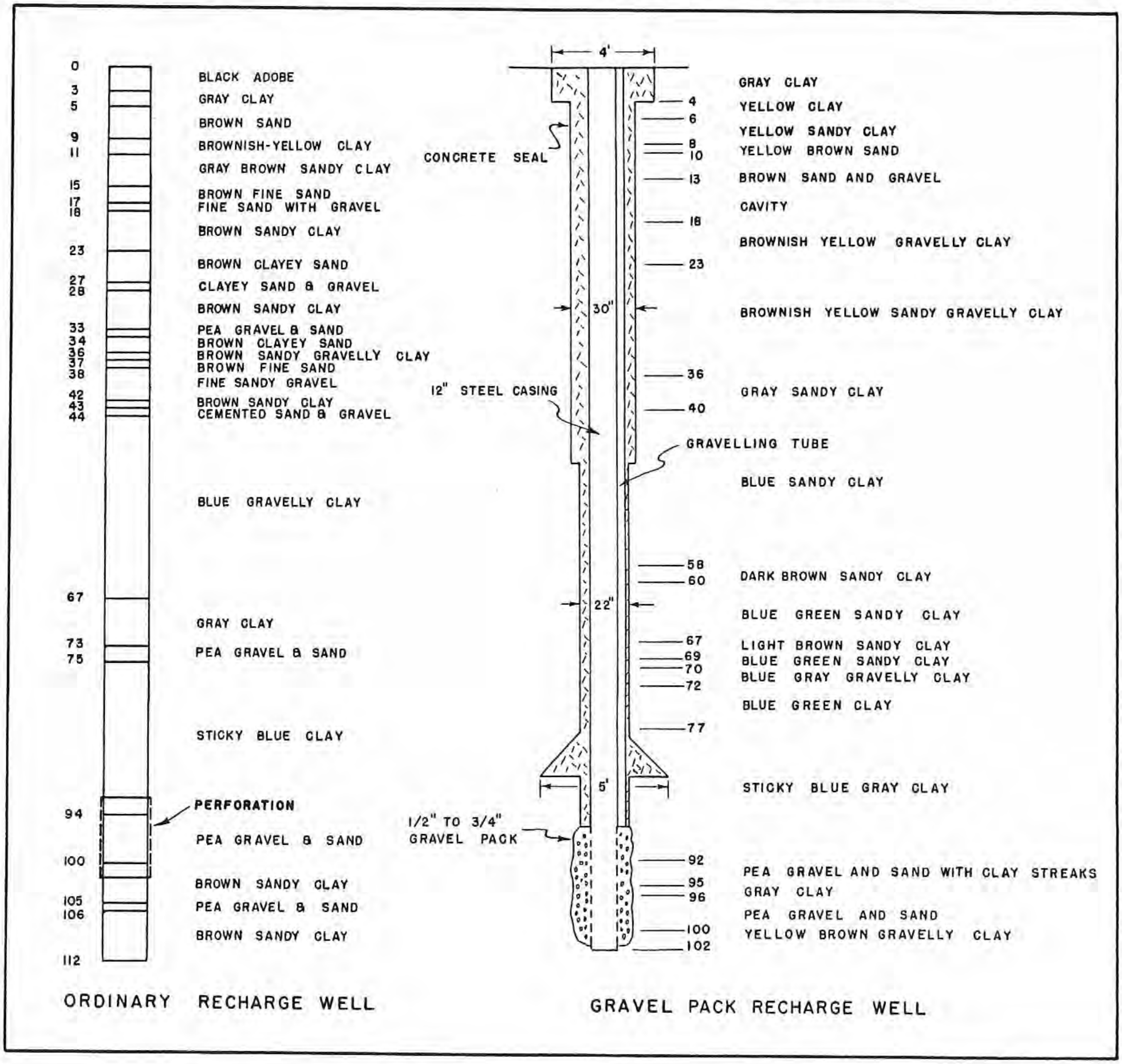


Fig. 5. Details of Recharge Wells Used in Experimental Studies

for approximately 12 months at rates of 17, 37, and 64 gpm without producing any evidence of damage to the well. The presence of non-packed observation wells at distances of 10 and 13 feet from the recharge well gave cause for some anxiety during experimental studies. Such wells, however, would not be present in a full scale ground water recharge operation.

In order to obtain samples and to observe the pressure pattern created in the aquifer during pumping and recharge experiments at Richmond, 23 6-inch observation wells were located at various distances from the recharge well, as shown in Table V (on opposite page). Wells appearing in the table in other than cardinal directions were originally referenced to the recharge well which failed.

Some typical piezometric pressure relationships during drawdown and recharge tests are shown in Figure 6 (on opposite page) for the Richmond well field. It is noteworthy that the recharge curve is essentially a mirror image of the drawdown curve, that the rate of pressure drop with distance from the recharge well is quite rapid, and that the pressure increase due to recharge with sewage occurs very near the recharge well.

The implications of Figure 6, as they concern the nature of suitable recharge wells, are worthy of brief elaboration. First from the shapes of the recharge and drawdown pressure curves it is evident that a gravel pack is necessary to stabilize the aquifer face. Under conditions of recharge, a particle of sand at the aquifer face is subjected to a pressure gradient which urges it to move outward into a zone of declining pressure and velocity in which, with distance, fine particles have been less and less affected by previous pumping of the well. This decrease in pore size prevents any profound migration of surface particles, with the result that movement is confined to minor adjustments involved in stabilization. When pumping is suddenly substituted for recharge and the direction of flow reversed, however, particles near the aquifer face are inclined to move in a direction of increasing void size and higher velocity gradients. If velocities are sufficient to transport particles at the aquifer face, a loss of aquifer material is inevitable and will continue until the aquifer face has receded beyond some critical distance, or until sand grains have bridged relatively large openings. Continued reversals of flow direction must inevitably lead to the creation of a void around the well screen of such diameter that radial velocities are no longer capable of serious injury to the aquifer face. The theory of gravel packing is simply that a void in the aquifer is purposely created during well construction and simultaneously filled with fine gravel. In this manner the effective radius of the well is increased to the point that velocity and pressure gradients across individual aquifer particles are no longer critical, while at the same time aquifer overburden is given support.

From the standpoint of aquifer stability the greater the diameter of gravel pack the better. the dotted curve in Figure 6, however, shows that clogging of the aquifer with suspended matter occurs near the aquifer face. Since it may become impossible to remove clogging by practical redevelopment procedures if velocities get too low, this means that there is theoretically some maximum permissible size of gravel pack. In order to get good aquifer stability and provide the maximum area of filter surface per unit of waste water recharged, however, the gravel pack should be as large as practicable, probably 4 to 5 or more feet in diameter with a 12-inch well. There seems to be no doubt that gravel packing of recharge wells is necessary, but there is no evidence that the type of gravel packed well required differs from that normally used in water well practice.

Results of Recharge Experiments. Experience with recharge of fresh water during the Richmond studies demonstrated conclusively that fresh water can be injected into the aquifer at important rates for long periods of time. For a period of 66 days fresh water was recharged at a rate of slightly more than 3 gal/min/foot of aquifer without difficulty, or without increasing recharge well head pressures beyond a steady state value of 15 feet above normal piezometric level. The recharge rate was then increased to 8.4 gal/min/ft of aquifer and fresh water injected for periods up to 33 days at a steady pressure of approximately 31 feet above normal ground piezometric level. Interruptions to maintain equipment and to remove tracers used in various studies occurred from time to time. During some of these interruptions the well was pumped at 400 gpm for periods ranging from 0.25 to 1.2 hours, but 8-1/2 months of operation showed that fresh water recharge in this case posed no particular problems.

Observations at recharge rates of 3, 3.8, and 8.4 gal/min/foot of aquifer showed steady state recharge pressures above normal ground water of 15, 19, 31 feet, respectively, indicating that the recharge rate is proportional to injection pressure.

Recharge with sewage effluents was accomplished at the same rates as with fresh water. Steady state pressures, however, did not develop. Progressive clogging, as discussed in a following

TABLE V

Location of Observation Wells With Respect To Gravel Packed Recharge Well

Well No.	Distance from Recharge Well	Direction From Recharge Well
1N	13 ft	North
2N	28 ''	''
3N	48 ''	''
4N	63 ''	''
5N	88''	''
6N	138''	''
1NW	45''	N15°W
2NW	63''	N53°W
1W	13''	West
2W	50''	''
1NE	39 ft	N15°E
2NE	45 ''	N34°E
3NE	63''	N53°E
4NE	106''	N70°E
1E	13''	East
2E	50''	''
1S	13''	South
2S	63''	''
3S	100''	''
4S	188''	''
5S	463''	''
1SE	190''	S32°E

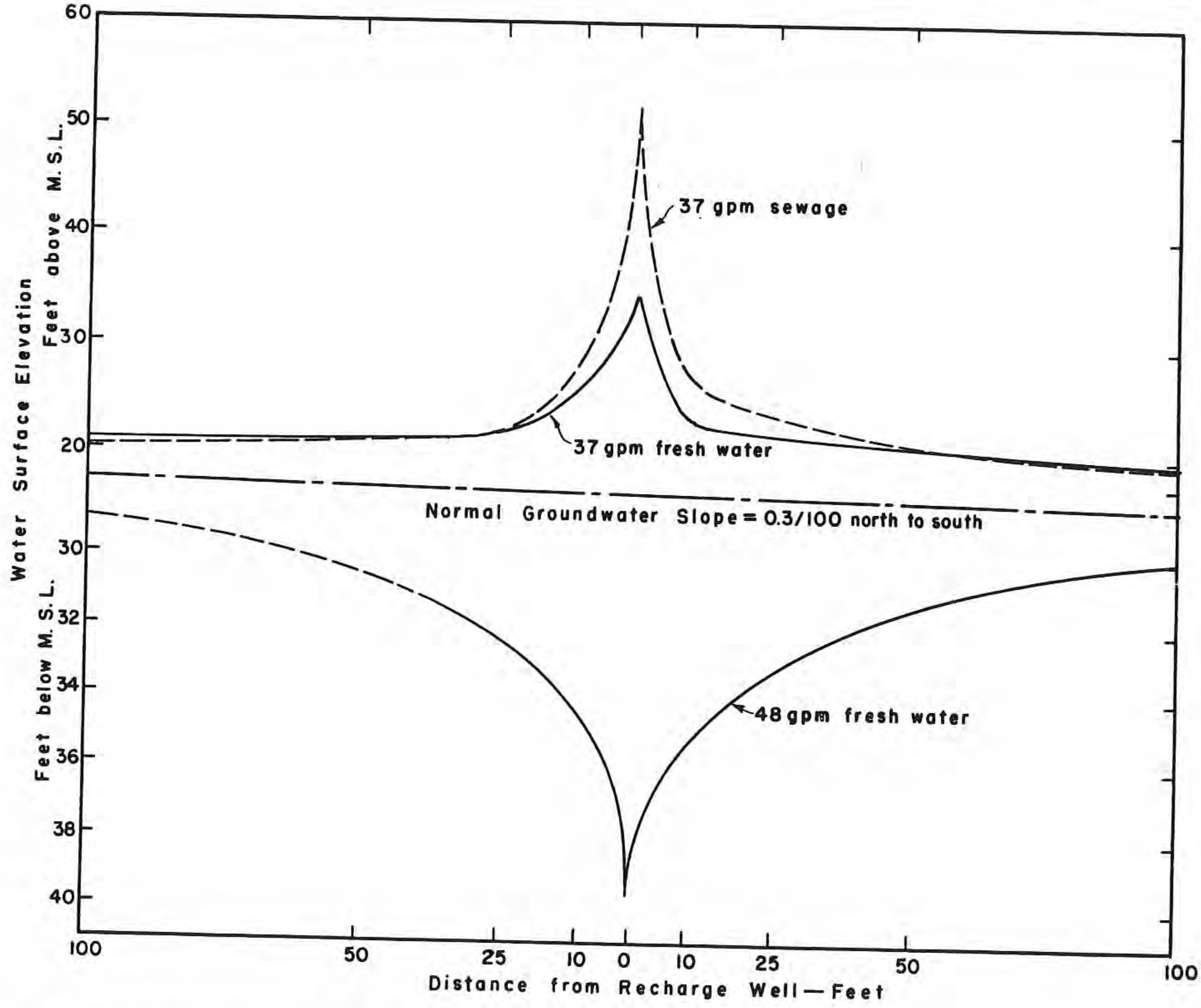


Fig. 6. Typical Drawdown and Recharge Pressure Curves Observed in Experiments at Richmond, Calif.

section of this report, produced a steady increase in well head pressure which showed no indication of levelling off prior to failure of the recharge well or of the injection equipment.

At Manhattan Beach recharge was accomplished with fresh water containing 5 ppm chlorine at rates approximating 4 gal/min/foot of aquifer under a pressure of but a few feet above normal ground water surface.

Tracer studies revealed the nature of radial movement of water in the shallow (4.4 ft average thickness) aquifer used in the Richmond studies. Because the aquifer was non-homogenous some portions of the recharged water moved much more rapidly than others in each of the four directions observed. The mass of injected water, however, formed a pressure intrusion which filled the aquifer voids by displacement of ground water, and which expanded in all directions as recharged progressed. Theoretically a uniformly expanding cylinder, the intrusion was actually considerably distorted in the direction of ground water flow as might be expected from hydraulic considerations. When sewage degraded water was injected, early clogging of the easiest avenues of flow resulted in a shifting flow pattern within the aquifer during recharge operations.

Studies of recharge of deep aquifers in a homogenous aquifer were accomplished by use of the model aquifer. In this case it was observed that the shape of the interface between recharged and ground waters at some distance from the recharge well was the same regardless of whether injection was accomplished through a well screen extending the entire depth of aquifer, penetrating only the top half of the aquifer, or open only in the bottom half of aquifer depth.

Clogging of Recharge Wells. The ground water recharge experiments at Richmond, California produced an appreciable amount of information on the rate and nature of recharge well clogging. From engineering experience with the flow of liquids through porous media it was possible to predict in advance that suspended matter in the recharge water would eventually clog the pores of the aquifer. It was believed that this clogging would occur in the aquifer face at the well screen and that, consequently, it might be possible to remove it by pumping. It was known that ion exchange could disperse clay but it was not expected that chemical incompatibility of recharge and ground waters would occur. As it turned out aquifer clogging was experienced by ion exchange, by biological growths, and by gases, as well as by suspended and dissolved organic solids.

Clogging as a result of ion exchange resulted only when a high concentration of sodium chloride was introduced as a tracer, and never as a result of any chemical incompatibility of normal recharge and ground waters. The sodium chloride dispersed the clay so rapidly that the recharge well head pressure increased more than a foot within a few seconds after the tracer entered the aquifer, and continued to rise at a precipitous rate. Aquifer permeability was quickly restored, however, by pumping the well until the injected sodium salt was removed.

Biological growths, usually Sphaerotilus, in pipes transporting settled sewage to the recharge site at abnormally low velocities were observed to increase the clogging rate found to be characteristic of sewage solids. Calculations of the amount of organic matter injected during a recharge run in which Sphaerotilus and other organisms were present, and of the amount removed during subsequent well re-development, showed that the organisms were undoubtedly growing in the well casing and perhaps in the aquifer face. The use of higher flushing velocities in the sewage delivery pipe lines readily removed Sphaerotilus as a problem in the Richmond experiments.

A somewhat unexpected contributor to recharge well clogging at Richmond was entrained gas which on occasion produced gas binding of the aquifer sufficient to make well redevelopment difficult. Fine gas bubbles were sometimes observed in carefully obtained samples taken from observation wells as far as 63 feet from the recharge well. Water pumped from the recharge well during such periods contained gas bubbles in amounts equal to 0.5 to 1.0 percent of its total volume. An analysis of this gas made with a mass spectrograph showed that it was more than 95 percent nitrogen, a little less than 3 percent carbon dioxide, 1.3 percent argon, and less than 0.3 percent oxygen. This concentration of argon supports a belief that air was the principal source of the entrained gas. The high nitrogen content supports this conclusion, while the absence of oxygen and the presence of an appreciable amount of carbon dioxide is evidence that biochemical decomposition took place underground. Precise observations of water temperatures over an extended period of time revealed that water pumped from the ground during well redevelopment averaged a fraction of a degree warmer than the recharge water which, in turn, was warmer than the normal ground water it displaced. Computations show that under the temperature and pressure conditions existing underground more than half a liter of nitrogen per hour could be liberated.

Inasmuch as the aquifer in the vicinity of the recharge well was filled with recharged water in contact with material previously saturated with slightly cooler water, the observed rise in temperature could be possible only if heat was continuously generated during recharge. There are only two possible sources of such heat - friction during injection and pumping, and biological decomposition of organic matter dissolved or suspended in the recharge water. Although the amount of heat from each of these sources is quite small the aggregate proved sufficient to cause the release of enough dissolved gas to produce a mild degree of gas binding of the aquifer.

By far the most significant cause of aquifer clogging was the suspended solids, chiefly organic in nature, and dissolved organic solids which came from sewage. Indications of progressive clogging began to appear as soon as sewage polluted water was injected. The recharge well head pressure increased at a uniform rate, and when greater amounts of suspended solids were introduced by varying the sewage strength, it became evident that clogging is proportional to the suspended solids content of the recharge water. That the dissolved organic solids likewise contributed to clogging can be deduced from the known nature of biochemical reactions although it was impossible to isolate their effect.

Figure 7 (on following page) shows observed rates of clogging, in terms of rise of well head pressure, in relation to pounds of suspended solids injected per day. Although there is some considerable scatter of data in the figure there is no doubt that the relationship is a straight line function. There are several reasons for the scatter observed.

1. All clogging was assumed to be the result of suspended organic solids, although it is known that dissolved organic solids may be precipitated by bacterial action, and that gas binding occurred in varying degrees.

2. Plotted values represent observed average amounts of suspended solids, which varied throughout the day, rather than the integral of the suspended solids which might have been obtained from continuous sampling.

In all studies from which data on rates of aquifer clogging were observed, equilibrium pressures were essentially established by fresh water recharge prior to the beginning of sewage injection. Changes in the shape of the recharge pressure curve are therefore the result of the changed nature of the recharge water, principally in the amount of characteristics of solids carried by it. Some important deductions can be made concerning the nature of clogging from a study of a typical pressure curve for the recharge well during sewage injection. Such a curve is shown in Figure 8 (on page 33), which represents the changes in recharge well head pressure during injection of a mixture of 73 percent fresh water and 27 percent primary settled sewage, and during subsequent fresh water recharge which was begun as soon as the well head pressure rose to the maximum acceptable value.

Figure 8 shows that a pressure rise became apparent immediately upon the injection of sewage. For two days this rise equaled 6.5 feet per day; then changed abruptly and continued at a fairly constant rate of 2.2 feet per day for seven days. Upon the substitution of fresh water for sewage, a pressure decline set in immediately and continued until the decrease had totaled six feet. Thereafter the pressure remained essentially constant until the close of the experiment.

Inasmuch as all of the pressure changes in Figure 8 are abrupt they must be considered significant; and since recharge water quality is the only other variable, they must be explainable in terms of water quality change. A logical explanation is that clogging of the aquifer face began as soon as suspended solids were introduced. As long as the biochemical nature of these solids was essentially constant, clogging increased at a rapid rate as indicated by the 6.5-foot per day rise in well head pressure. By the end of two days, however, a balance was established between the rate of increase of clogging due to the accumulation of raw solids at the aquifer face, and the rate of decrease in the clogging potential of solids undergoing biological decomposition. This balance then remained in effect until the start of fresh water injection. Thereafter, biochemical changes continued to reduce the clogging potential of solids in the organic mat at the aquifer face, but without the addition of fresh solids the net result was a decrease in clogging. By the end of about two days the substrate approached exhaustion and clogging remained constant at some residual potential of the partly decomposed organic solids. It is possible that a change in gas binding of the aquifer by re-dissolution of free gases when colder water was injected may have contributed to the observed decline in pressure.

Redevelopment of Clogged Wells. Experiments having shown that suspended and dissolved organic solids will clog an aquifer at a rate proportional to the amount of such solids present, although fresh water may be injected for long periods without difficulty, it is evident that if sewage plant effluents are to be reclaimed by direct recharge into aquifers:

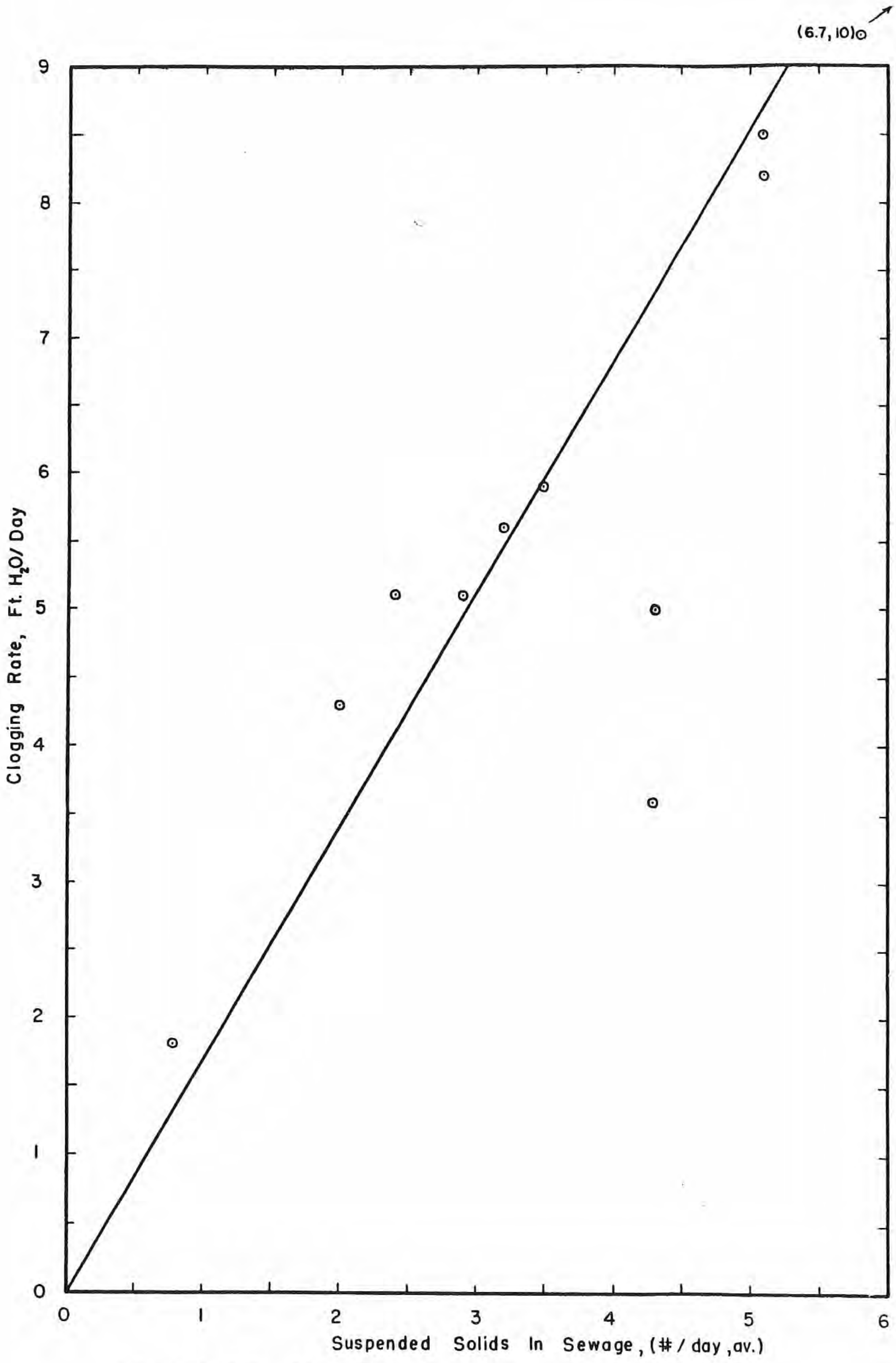


Fig. 7. Relationship of Suspended Solids to Rate of Well Clogging

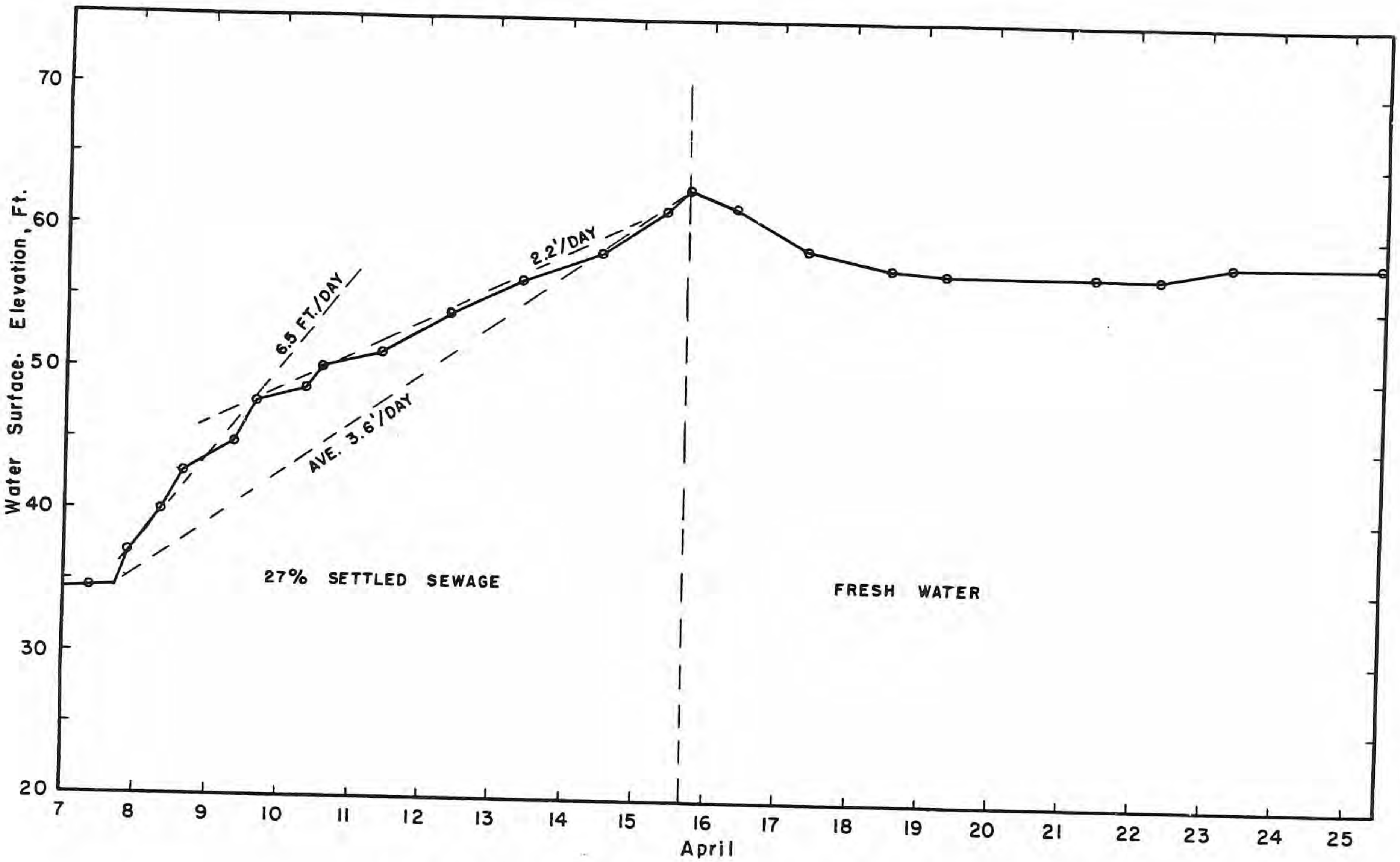


Fig. 8. Pressure Change in Recharge Well due to Clogging

1. They must be clarified and dissolved organic matter perhaps stabilized to a greater degree than is presently accomplished by sewage treatment works; or

2. Recharge wells must be redeveloped periodically in order to remove clogging.

In either case filtration to remove suspended solids and to render dissolved organic matter essentially stable biochemically is involved. Underground filtration, however, would seem the most economical provided the filter can be readily cleaned. The Richmond studies therefore included numerous experiments in recharge well redevelopment.

The isolated case of clogging due to dispersion of the clay fraction of the aquifer by ion exchange was, as previously noted, readily overcome by simple pumping of the recharge well, at a rate equal to about is safe yield, until the incompatible material previously injected had been removed. Pumping at such a rate, or even at rates great enough to endanger the aquifer, however, were ineffective in removing clogging due to organic solids. All successful redevelopments to remove clogging resulting from sewage injection were accomplished with the use of chlorine although not every experiment in well chlorination resulted in the satisfactory removal of clogging. A proper combination of chlorine dosage, extent of penetration of chlorine into the aquifer, contact period, and rate of pumping had to be determined by trial. It was found that redevelopment procedures must be vigorous enough to restore the original equilibrium well head pressure under fresh water injection or the capacity of the well to receive sewage is not re-established.

In the Richmond experiments chlorine dosage varied from 150 to 1100 ppm injected over periods ranging from 40 to 156 minutes. Contact periods ranged from 0.1 to 2.0 days, and discharge rates varied from 20 to 94 gpm for periods of from 20 minutes to several hours. An analysis of experiments which resulted in successful removal of aquifer clogging yields the following requirements for satisfactory redevelopment of the Richmond Well.

1. Chlorine dosage should be sufficient to provide a slight residual in the first water discharged when pumping begins at the end of a period of contact. Dosages of about 250 ppm available chlorine were required.

2. Chlorine should be injected until a residual appears at a distance of 10 to 13 feet from the recharge well. This involved injection at 8.4 gal/min/foot of aquifer for a maximum of two hours.

3. A contact period of about half a day is necessary.

4. Pumping at rates equal to the safe yield of the well for 20 minutes to 4 hours is required to redevelop the well, the shorter periods being sufficient to remove clogging unless gas binding is serious. In cases of gas binding the redevelopment procedure was repeated with a reduced amount of chlorine and a shorter time of contact, necessitating a total pumping time of 3 or 4 hours. The rate of pumping, or safe yield of the well, was taken as 60 to 80 gpm, or about 18 gal/min/foot of aquifer, on the basis of previous drawdown tests.

A field scale recharge operation would not, of course, involve nearby sampling wells which would enable the operator to determine the extent to movement of injected chlorine, although the theoretical distance of travel in any period of time could be calculated. With sufficient operational experience, however, it should be possible to use the well head pressure drop during chlorination as a control test in judging the degree of chlorination necessary. Figure 9 (on following page) illustrates the typical manner in which well head pressures dropped when injection of chlorine followed immediately upon the injection of sewage. It was observed many times in the Richmond experiments that after a pressure increase of about one foot, over a period of 20 minutes, a pressure drop of ten feet occurred in approximately 2.5 hours.

The cause for the pressure decrease shown in Figure 9 seems fairly obvious in view of the ability of chlorine to coagulate organic matter. The permeability of the mat of organic solids at or near the aquifer face is progressively increased by the action of chlorine, until some maximum limit is reached.

Attempts to redevelop the recharge well at Richmond by surging without the use of chlorine proved unsuccessful and when chlorine was used surging was unnecessary. Proposals to use compressed air at 200 to 400 psi for redeveloping wells clogged as a result of injecting silt laden waters have been seriously advanced but no data on the results of such treatment have been released. If the treatment is not too drastic it is possible that it may be effective on inorganic materials, but it is extremely doubtful that a biologically active organic filter mat could be removed from the aquifer face by compressed air. More likely it would result in air binding of the aquifer.

Operation of Recharge Wells. In the Richmond studies no difficulty was encountered in injecting fresh water into the ground water. Reports from

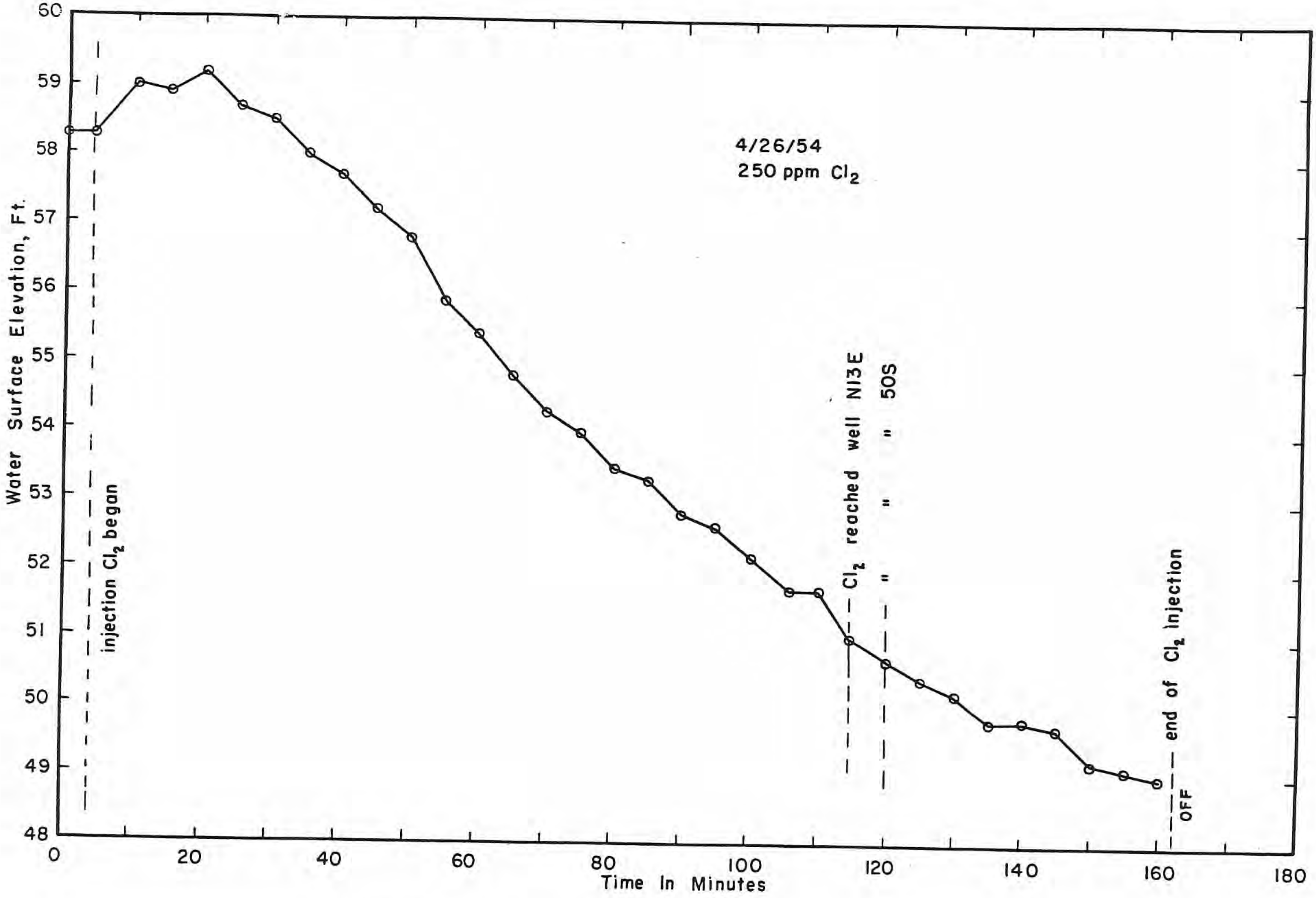


Fig. 9. Pressure Changes in Recharge Well During Chlorine Injection

the experiment at Manhattan Beach, however, show that in that instance the addition of 5 ppm of chlorine is considered necessary to prevent clogging of injection wells under continuous fresh water recharge. Experiments in prechlorination of sewage degraded water with 10 ppm available chlorine were conducted at Richmond. Results indicated that under such an operational procedure redevelopment might be accomplished with a lesser degree of chlorination, but the total use of chlorine was increased by some four hundred percent.

Several combinations of primary settled sewage and fresh water were used in the Richmond experiments. Most of the work was done with 20 percent sewage and 80 percent fresh water. This combination was used to simulate, in terms of suspended solids and BOD content, the final effluent from a sewage treatment plant involving secondary treatment. It was recognized, of course, that the solids in primary sewage are less stable biochemically than the solids in a final effluent. This instability, however, should result in a clogging potential greater than that of a final effluent, hence experimental conditions should be more rigorous than those to be expected in a full scale operation.

With the 20 percent sewage and a permissible well head pressure increase of 60 feet, it was necessary to redevelop the Richmond recharge well every 7 or 8 days. Approximately one working day was then required for redevelopment operations, including 3 or 4 hours of pumping at rates of 60 to 80 gpm. Several successful well redevelopments were accomplished with pumping periods as short as 20 to 30 minutes, but the longer period was more characteristic of the Richmond experience. On the same basis of 3 or 4 hours of pumping, some 4 percent of the recharged water was returned to the surface, carrying with it flocculent organic matter removed from the aquifer face.

In experimental studies the well discharge was returned to the sewer. A more practical approach to the problem of disposal of redevelopment water, together with a general discussion of recharge well operation is presented in a subsequent section of this report which deals with the engineering aspects of ground water recharge.

PUBLIC HEALTH AND WATER QUALITY ASPECTS OF WASTE WATER RECLAMATION

Status of Knowledge of Pollution Travel

The record of human catastrophe as a result of man's ignorance of the relationship of polluted water to disease is so long and well documented that those who today are responsible for protecting the public health or safeguarding the hygienic quality of waters are understandably cautious in any case where the true danger of water pollution is unknown. Such a circumstance has long characterized the matter of introducing sewage underground, hence if planned reclamation of such waste waters by ground water recharge is to become practicable the conditions under which it may be safely accomplished must be clearly understood.

Cesspools and septic tanks have returned sewage effluents to the soil for centuries, but since the advent of modern knowledge of and concern for the public health, acceptance of such procedures becomes an increasingly uneasy one as the density of population increases. Instances of pollution of water supplies by underground movement of pollutants either through known or unsuspected channels are well authenticated. Consequently laws presupposing the danger of free travel of harmful bacteria and toxic chemicals have been enacted in most states and may be expected properly to remain in force until the fundamentals of pollution travel are better defined. The laws of the State of California for example, specifically prohibit the discharge of any waters unfit for human consumption into underground water bearing formations suitable for use as a source of domestic water supply. Enforcement of this restriction is often difficult. In some areas where soils are too tight for satisfactory performance of septic tanks, which depend upon subsurface spreading of effluent, illegal drainage wells have been drilled to intersect the ground water. Whether these in fact constitute a serious menace to the public health is a question that many are inclined to argue.

Two distinctly different aspects of pollution travel are involved in ground water recharge by surface spreading, direct recharge, and over-irrigation, as well as in the leachings from septic tanks, privies, cesspools, surface waters, and refuse dumps. They concern: 1) the movement of bacteria and chemicals downward with percolating water; and 2) the lateral movement of such pollutants once they have entered the ground water, either along with percolating water or by direct recharge.

Prior to the experimental work described in the following section of this report a variety of observations of the underground travel of pollution had been reported. Some of these were the result of carefully conducted investigations, while others represent gross observations of the fact of pollution travel without providing evidence of the geological and hydrological conditions under which such movement took place. As a result, much of our experience with the movement of bacteria and chemicals with underground water has served more as a danger signal than as a scientific basis on which a program of waste water reclamation might be founded and under which ground water quality is adequately maintained.

The literature cited in several reports of the University of California (54) (10) (4) (6) may serve to highlight our knowledge of the underground behavior of bacterial and chemical pollutants. In the following summary the list of authors who have made significant contributions to the subject is by no means complete. Nevertheless, it may be sufficient to establish a background for the experimental work subsequently presented, and to help the reader to understand why such experimental work and other investigations yet to be undertaken are deemed worthy of pursuit.

Movement of Pollution With Percolating Waters.

Observers are generally in agreement that pollution is not laterally extended to any important degree when the water which transports it infiltrates the ground surface and percolates downward through soil above the ground water table. The extent of vertical travel of micro-organisms, therefore, becomes the most important factor in determining the public health danger involved when sewage effluents are added to the ground water by surface spreading, and in defining the minimum safe distance between the ground surface and the water table in any particular instance. In this matter, various investigators have arrived at a variety of tentative conclusions. The general view (15) (16) (17) has been that waste water reclamation by surface or subsurface spreading is safe, from the standpoint of impairment of ground water quality, as well as practical when the waste water is first subjected to a high degree of pretreatment.

Several investigators have experimented with more highly polluted wastes. Some of the earliest and most significant work was done by Kligler (55) who made careful observations of the movement of coliform organisms and other pollutants, during both rainy and dry seasons, from some 50 pit privies constructed in different soils. Wells located 25 and 40 feet from the pits showed no contamination, and examinations of the soils led to the general conclusion that pollution may extend only about 5 feet into the soil. Caldwell (56) later concluded from careful studies of human excreta in latrines that coliform organisms move only one to five feet in dry or slightly moist soils. In the Dutch East Indies, however, investigators (57) reported finding coliform organisms in soil two years after contamination, decreasing in numbers down to 9-13 feet but increasing again as the ground water level was approached. In inhabited areas, sewage bacteria were found as deep as 33 feet below the soil surface, leading the investigators to conclude that purification in the soil is less profound than has been claimed.

Movement of Pollution With Ground Water. Although considerably more opportunity has been afforded to study the travel of bacterial and chemical pollutants with ground water movement than with percolating waters, published reports reveal that only little is known of the conditions under which lateral travel of such materials might occur. All investigators seem to agree that pollution travels farthest in the direction of ground water flow and that chemicals travel much farther than bacteria in a water bearing stratum. This latter conclusion seems evident from general experience which repeatedly shows that dissolved matter moves more readily that particulate matter through a porous medium of relatively small pore size. Stiles and Crohurst (58) showed this to be the case in the movement of water from sewage polluted trenches. In a sand of effective size 0.13 mm coliform bacteria traveled 65 feet in 27 weeks, while chemicals traveled 115 feet in the same period. In carefully conducted tests these same researchers (59) observed the movement of coliform organisms and of the chemical, uranin, from polluted trenches intersecting the ground water. They found bacteria 232 feet and uranin 450 feet from the trench, with both bypes of pollution persisting for 2-1/2 years. In both studies (58) (59) they reported movement in the direction of ground water flow only, more extensive travel in wet weather than in dry, and a tendency for pollution to stay in the capillary fringe of ground water when the water table lowered. Similar experiences are reported by Hofman (60) in Germany, and by Dyer and Bhaskaran (61) in India.

Ditthorn and Luerssen (62) reported on the introduction of Bacillus prodigiosus into an aquifer of porosity 32.8 percent at a point 69 feet from a well. The bacteria appeared in the well on ten consecutive days, beginning with the ninth day, and were found as long as 30 days after injection ceased.

A series of studies in which latrines were bored 3 to 5 feet into ground water was conducted by Caldwell (63) (64) (65). In one case involving soil of an effective size 0.08 mm, coliform organisms penetrated 10 feet and anaerobes 50 feet, while chemical pollutants were observed 300 feet down the stratum. In another case, a latrine, penetrating an aquifer in which the ground water was moving 10 to 16 feet per day, was lined with perforated boards supporting fine soil. Test wells 10 feet away showed no coliform organisms, although odors, foaming, and pH changes were indicative of the movement of other materials. In one pit, extending three feet into a ground water moving 13.3 feet per day, coliform organisms extended past 80 feet from the point of contamination but regressed to 20 feet because of soil defense. This phenomenon was observed in another pit (66) in which the initial rate of flow of pollution from the latrine approached the ground water velocity, then receded as clogging developed. In this case bacteria traveled 35 feet and chemicals traveled 90 feet.

Various distances of travel have been reported, although most of the observations are of gross phenomena rather than the result of planned and rechecked experiments. Warrick and Tully (67) cite an instance of river water entering abandoned wells, from where it traveled 800 feet, probably in fissured strata, to city wells and caused 1100 cases of dysentery, and typhoid. Salt introduced as a tracer moved through the 800 feet in 17 hours. In another instance (68) activated sludge effluent was traced from percolation beds to a spring 1500 feet away, passing through fine sand in a narrow stream. Coliform organisms were absent after 400 feet, but iron bacteria flourished at the spring. Ammonia dropped from 12 ppm to 6 ppm in 1400 feet, while nitrates increased from 0.04 to 10 ppm.

A few reports indicate little travel of bacteria. Meinzer (69) suggested that the travel of bacteria seems limited in sands but cited a need for further exacting and conclusive investigations into this aspect of recharge. Sampson (70) reported in 1934 that wells 150 feet from percolation beds produced sterile water. In Germany Austen (71) found bacteria disappearing in a few meters in seepage moving at a velocity of about 1 meter per day. Holthusen (72) described the results of five years of operation of 270 wells in a 5500-acre collecting ground on which 29 mgd of water from a river and drainage ditch were applied. Each well was surrounded by a 55 yard collecting strip. No coliform bacteria appeared in the wells and the bacteria count increased only from 0 to 2 per ml in water traveling at a rate of 85 meters in two months. Water temperature increased 0.5°C, and the travel of chemicals produced an increase in iron, manganese, and carbon dioxide.

As might generally be expected chemical pollutants travel farther than bacterial. European, especially German, experience reveals many instances of the travel of chemicals with ground water. Lang (73) described three instances in which ground water supplies were abandoned as a result of wood tar residues traveling 197 feet, picric acid wastes traveling several miles, and pickling liquors traveling an unspecified distance. He also cited an instance of leachings from an old garbage dump reaching wells 1476 feet away, causing an increase in total solids from 360 to 552 ppm, and of hardness from 190 to 272 ppm. Some eight years later Lang (74) reported a travel of picric acid wastes of three miles in 4 to 6 years. Wells 2000 feet downstream from cooling ponds showed a temperature rise and an increase in manganese, hardness, and iron. In other instances, garbage dumped in a sand pit continued to pollute wells 2000 feet away 15 years after the dumping of garbage had ceased; and chlorinated sewage from a leaking pipe caused phenol tastes and fungal growth in wells 300 feet away. Dye added to the sewage traveled 300 feet in 24 hours. Rossler (75) recently observed an increase in chlorides hardness, and manganese in wells below a garbage dump after ten years.

Austen (76) recorded the pollution of wells in Breslau by seepage from a river 50 meters away, and reported tests which show artificial recharge to be productive of changes in the chemical composition of well water, notably in iron and hardness.

Similar data have been observed in the United States. At Vernon, California (77) chemical contamination traveled three to five miles. In Michigan (78) chromate wastes advanced through sand to pollute wells at a distance of 1000 feet in three years. Davids and Leiber (79) found aquifers contaminated with 40 ppm of chromium as a result of discharging chromium wastes into leaching pits.

Caldwell (63) found chemical pollution traveling 47 feet in a width of 25 feet and a depth of 7 feet in ground water moving only 0.2 to 1.5 feet per day. Calvert (80) reported an increase in hardness, calcium, manganese, total solids, and carbon dioxide in wells 500 feet from an impounding pit for liquor from a garbage reduction plant.

Sayre and Stringfield (81) found phenol wastes traveling 1800 feet in the ground water in one instance and failing to penetrate 150 feet in another. Muller (82) reported two cases in which gasoline escaped into the ground and ultimately produced detectable odors in wells as far away as two miles. Fox (83) using radioactive rubidium chloride to trace underground brine in Egypt's desert found radioactivity in outflow springs within 5 days. Sayre and Stringfield (81) recalled an incident where weed killer moved with ground water in the Los Angeles area more than 20 miles in six months. Some wells near the source of original ground water contamination showed signs of contamination three years later.

The movement of salt brines with ground water seems especially pronounced. Eight hundred kg of sodium chloride placed in a sand pit soon reached a well 71 meters away. Sumps containing oil field brine (84) contaminated ground water so that wells 1/4 mile away became unfit for use in irrigation. Salt placed in a cesspool (85) reached a well 200 feet away in 24 hours. A summary of the foregoing observations of the travel of bacterial and chemical pollution with ground water movement is presented in Table VI (on following page).

It is significant that most of the observations of pollution travel which have involved controlled experiments have been concerned with the movement of bacteria, while data on chemical travel are predominantly gross observations of travel with ground water moving through strata of little known nature, or represent observations of chemical pollution taken somewhere along a path of unknown extent. This is true of the data summarized in Table VI as well as of that obtained in recent experimental studies hereinafter discussed. There are a number of reasons why this should be the case. In the first place water pollution by domestic sewage has long constituted a more serious threat to the public health than have chemical wastes from industries. In addition, the chemicals in domestic sewage differ little from those in normal water supplies, and hence are of little public health significance in comparison with micro-organisms. Furthermore, the cost of a scientific investigation of the magnitude and duration necessary to establish the limits of travel of chemicals underground would be grossly out of scale with the present urgency of the problem and with the present benefits to be derived from its solution.

With an increase in industrial use of water and a more intensive overall utilization of available supplies, the long range effect on the chemical quality of ground waters may become a more important consideration in water reclamation than danger to the public health from bacterial pollution. In that event it may be necessary to exclude an increasing proportion of industrial

TABLE VI

Summary of Distances of Travel of Pollution Reported in Literature Cited

Nature of Pollution	Pollutant	Observed Distance of Travel	Time of Travel
Sewage polluted trenches intersecting ground water	Coliform bacteria	65 feet	27 weeks
	Chemicals	115 feet	. . . . .
Polluted trenches intersecting ground water	Coliform bacteria	232 feet	. . . . .
	Uranin	450 feet	. . . . .
River water in abandoned wells	Intest. pathogens	800 feet	17 hours
	Tracer salts	800 feet	17 hours
Sewage in bored latrines intersecting ground water	Coliform bacteria	10 feet	
	Anaerobic bacteria	50 feet	
	Chemicals	300 feet	
Sewage in bored latrines lined with fine soil	Coliform bacteria	10 feet	
Sewage in bored latrines intersecting ground water	Coliform bacteria	35 feet	
	Chemicals	90 feet	
Sewage in bored latrines intersecting ground water	Coliform bacteria	80 feet; regressed to 20 feet	
Coliform organisms introduced into soil	Coliform bacteria	50 meters	37 days
Sewage effluents on percolation beds	Coliform bacteria	400 feet	
	Ammonia	1400 feet	
Sewage effluent on percolation beds	Bacteria	150 feet	
Sewage polluted ground water	Bacteria	A few meters	
Introduced bacteria	*Bacillus prodigiosus*	69 feet	9 days
Chlorinated sewage	phenols, fungi	300 feet	
	Dye	300 feet	24 hours
Industrial Waste	Tar residues	197 feet	
	Picric acid	several miles	
Garbage leachings	Misc. leachings	1476 feet	
Industrial wastes	Picric acid	3 miles	4-6 years
Industrial wastes in cooling ponds	Mn, Fe, hardness	2000 feet	
Garbage leachings	Misc. leachings	2000 feet	
Garbage reduction plant	Ca, Mg, CO_2	500 feet	
River water	Fe, Misc. chemicals	50 meters	
Chemical waste	Misc. chemicals	3-5 miles	
Industrial wastes	Chromate	1000 feet	3 years
	Phenol	1800 feet	
	Phenol	150 feet	
Salt	Chlorides	71 meters	
Oil field brine	Chlorides	1/4 mile	
Salt	Chlorides	200 feet	24 hours
Gasoline	Gasoline	2 miles	
Weed killer wastes	Chemical	20 miles	6 months
Radioactive rubidium chloride	Rubidium		5 days

Note: Chemicals observed to travel 2 to 30 times as far as bacteria.

waters from those to be reclaimed by ground water recharge, in which case the amount of reclaimable water is curtailed, or to require a more elaborate pre-treatment of waters to be recharged underground, in which case the economics of water reclamation may be adversely affected.

In any event the distance of underground travel of chemicals as observed in instances reported in Table VI, and implied by the results of recent experiments means that waste waters involving toxic or objectionable chemicals are unsuitable for reclamation by ground water recharge. In fact, it seems probable that only domestic sewage plant effluents, food processing waste waters, excess flood waters, and similar materials represent available recharge waters.

Experimental Studies of the Travel of Bacteria

As previously noted in this report a number of experimental studies of the feasibility of waste water reclamation by ground water recharge have been conducted in recent years. A major concern of all those which involved the reclamation of sewage has been the public health hazard which might result from the underground movement of bacteria. Specific purposes of the Whittier and Azusa (17) (28) included, an evaluation of percolation through soil as a means of removing the bacterial pollution of waters spread on the soil surface. The Lodi studies (10) sought among other principal objectives to determine the extent to which mineral and organic matter (including bacteria) penetrate a soil; the changes in mineral and organic characteristics of both soil and water during percolation; and the degree of pretreatment of sewage prior to spreading necessary to protect underground water supplies. Spreading studies (6) which grew out of the Lodi work were designed to determine the extent of bacterial build up in the soil and its relation to the concentration of bacteria in the percolating liquid, as well as the depth of penetration of organic matter and the degree of bacterial removal by different soil types. The primary purpose of the Richmond studies (4) of direct injection of water into underground formation was to determine the rate and extent of travel of pollution with ground water flow.

Experimental studies presently under way are likewise concerned to some degree with the public health aspects of waste water reclamation. One of these, which grew out of the Lodi (10) and spreading studies (6) and which is being conducted by the University of California at Berkeley under a grant-in-aid from the National Institutes of Health of the Public Health service, is expected to yield significant information on the mechanism of removal of bacteria from percolating water. Another (86) being carried on by the University of Southern California under the sponsorship of the California State Water Pollution Control Board, will focus attention on the public health aspects of current industrial and agricultural utilization of sewage effluents.

Movement of Bacteria with Percolating Water.

In spreading tests at Whittier a secondary sewage containing a coliform concentration of more than 110,000 per 100 ml was spread at a rate of 1 cu ft per square foot per day for a period of some 12 days. Coliform densities of 40,000 per 100 ml were observed at a depth of three feet in the soil but none were observed at greater depths. At Azusa an applied secondary sewage having an MPN of more than 120,000 coliform organisms per 100 ml produced effluents at 2-1/2 and 7-foot

TABLE VII

MPN of Coliform Organisms As a Function of Depth in Hanford Fine Sandy Loam at Lodi, California

Basin	Sewage Effluent Spread	Avg. MPN at indicated Depth						
		Surface	1 ft	2 ft	4 ft	7 ft	10 ft	13 ft
A	Primary	414×10^4	1.6	32*	0.6	0	0	
	Final	179×10^3	1.2	285*	2.1	0	0	
B	Primary	570×10^4	20	0	0	0	0	0
	Final	188×10^3	482	5.6	0.5	0.2	0.1	0
C	—	—	—	—	—	—	—	—
	Final	188×10^3	148	305	2.0	0.2	0.1	0.3
D	—	—	—	—	—	—	—	—
	Final	164×10^3	0.2	—	—	0	—	0

*Sand channel from surface to 2-foot depth.

depths having an MPN of but 60. When primary sewage was applied, however, counts as high as 1.2 x 10^6 were observed at 7 feet below the ground surface. In more recent studies conducted by the Los Angeles County Flood Control District high rate infiltration of secondary effluent into beach sand was observed. Coliform concentrations of 70,000 organisms per 100 ml were reduced to 700 per 100 ml in 12 feet of sand depth.

Four of the spreading basins used in the Lodi study were equipped for percolant sampling at depths of 1, 2, 4, 7, 10, and 13 feet below the ground surface. Basins designated as A, B, C, and D in Table III were spread at various times with primary settled sewage and with final effluent with the results shown in Table VII (on preceding page).

From Table VII it is evident that a very definite inverse relationship exists between coliform count and depth of soil through which the applied sewage has percolated. Furthermore, the disappearance of bacteria with depth is extremely rapid. Somewhere between the 4- and 7-foot sampling depths the bacterial quality of the percolating sewage in all cases dropped below the USPHS minimum standard for potable water of 1.0 coliforms per 100 ml.

Another significant fact growing out of the Lodi experiments, and illustrated by Table VIII, is that the number of coliform organisms penetrating one foot or more, as measured by tests of the percolating liquid, is essentially independent of the intensity of pollution of the waste water spread. Lysimeter studies (6) of the Lodi soil and four other pervious soils showed that the removal of bacteria is most pronounced in two zones. The first zone is a surface stratum 0.5 to 1.0 cm in thickness which represents essentially a filter mat of organic matter removed from the infiltrating sewage. The second is a typical limiting zone which builds up at various depths below the soil surface and which is characterized by a steep hydraulic gradient. In as much as such a limiting zone has been observed in the Bakersfield and other studies in which only fresh water was spread, it is believed that this limiting zone results from a migration of fines and from other phenomena not of a biochemical nature. Limiting zones developed at from 10 to 50 cm below the surface of various soils used in the lysimeter studies.

The effectiveness of the two zones in removing bacteria can be shown by the number of coliform organisms observed in the soil itself at various depths below the surface. Figure 10 shows characteristic concentrations of coliform organisms left by infiltrating sewage in a thin layer of the surface of soils tested in the lysimeter studies. The high bacterial count at the surface, of course, indicates a large removal of organisms from the applied sewage, while the relatively constant high numbers at depths of from 2 to 7 mm shows a continued rapid removal of organisms in proportion to depth. The actual organisms count, however, represents a bacterial buildup in the soil which is a function of the intensity of pollution of the applied sewage; the rate of infiltration; and bacterial survival.

Both the surface and limiting zone are illustrated in Figure 11, which shows graphically the nature of bacterial counts in Hanford fine sandy loam (6) when a lysimeter was spread with sewage containing an average MPN of 1.1 x 10^8 organisms. A large concentration of organisms developed at the soil surface. Thereafter a decrease occurred in the 1 to 4 cm range of soil depth, indicating that in that region bacteria were continuing to travel downward with the percolating liquid. Below 4 cm the removal increased with depth, as evidenced by a buildup of organisms in the soil to a maximum of about 9.1 x 10^8 organisms per gram of soil at 25 centimeters. At an observation point 47 cm below the surface soil samples contained an MPN of 3.42 x 10^8 coliform organisms per gram, but at 65 cm the number had dropped to 2.84 x 10^6. This could mean either that bacteria moved downward quite freely with percolating water or that they were left behind and did not get beyond the 47 cm observation point in any important numbers. Coliform counts on the percolating liquid over a period of many weeks showed the latter to be the case. At 47 cm the liquid contained an MPN of 8.4 x 10^7 organisms per 100 ml, while at 65 cm the count was but 230 per 100 ml. Tensiometers showed that between the two depths a steep hydraulic gradient existed, indicating the pressure of a limiting zone.

It should be noted that values given for soil in the foregoing discussion are expressed as Most Probable Number (MPN) of coliform organisms per gram of dry soil, while the intensity of pollution of the liquid is expressed as MPN per 100 ml of liquid. No attempt was made to evaluate the numbers of soil organisms in terms of percentage removal from the carrier liquid and of survival in the soil. Tests were run, however, which identified the organisms in both soil and liquid as E. Coli rather than soil organisms of the coliform group. The study demonstrated that a lightly polluted effluent may emerge from a highly polluted soil. The contaminant potentialities of this polluted soil in the event that the water table rises to intersect it were not explored but they do not seem to be serious in fine textured soils. Previous careful studies by Stiles and Crohurst (59) revealed a tendency for

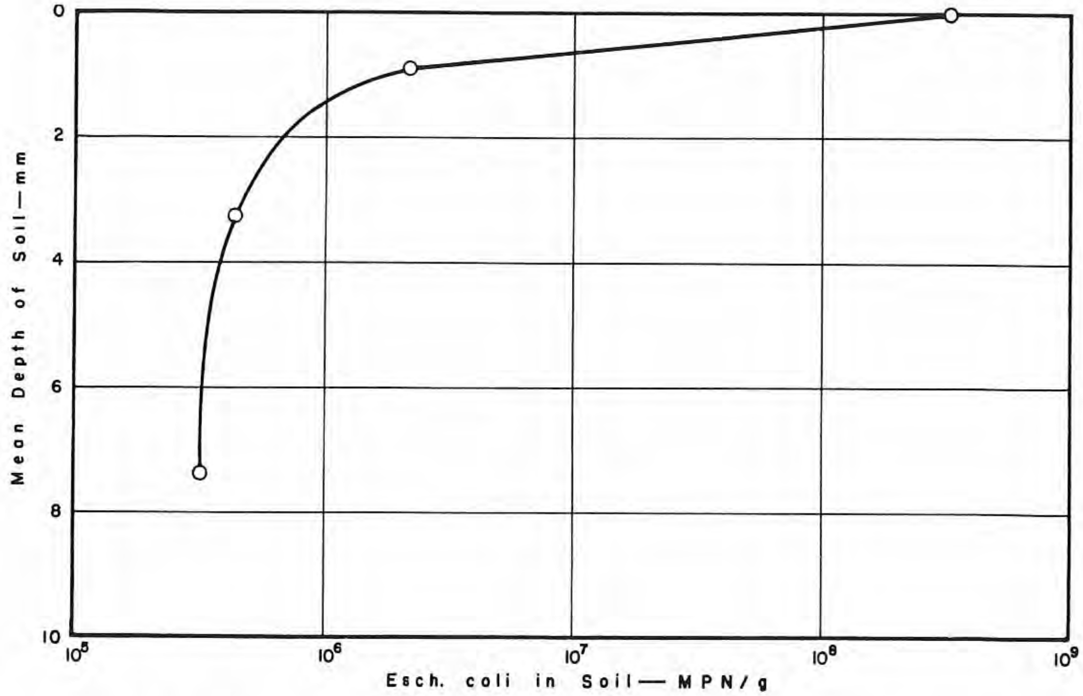


Fig. 10. Concentration of Coliform Organisms Near Soil Surface.

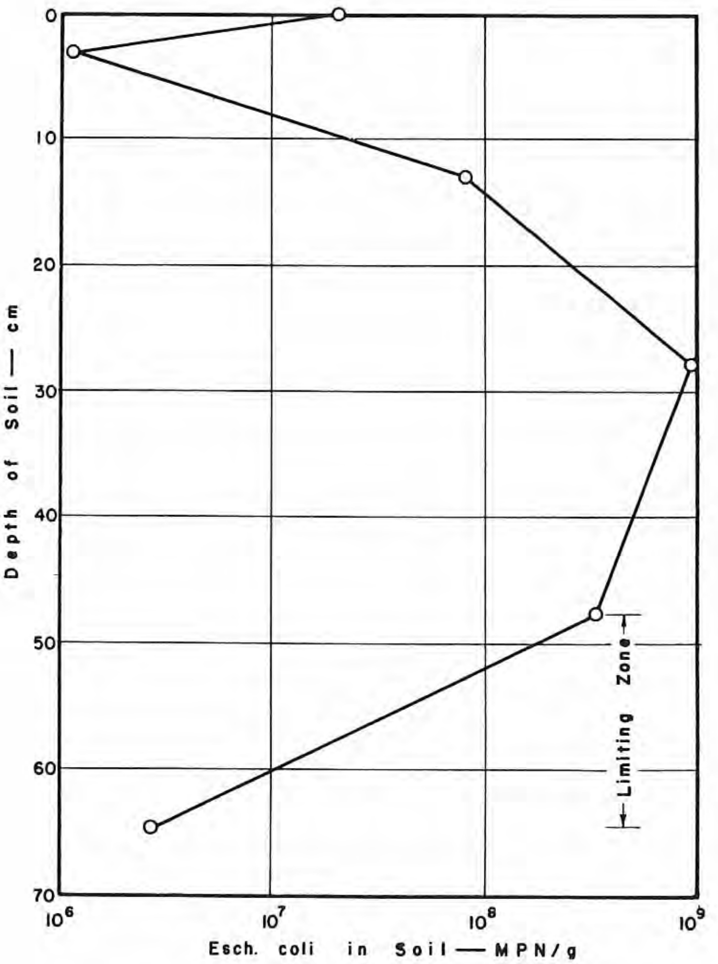


Fig. 11. Concentration Of Coliform Organisms With Depth In Hanford Soil

pollution to stay in the capillary fringe of ground water when the water table lowered.

In coarser materials it is possible that pollutants picked up by rising ground water coming in contact with polluted soil might move laterally with ground water flow to a limited extent, as discussed in the following section of this report, but it seems unlikely that any downward movement would constitute a greater pollutional hazard than that of the percolating water which originally deposited the pollutants. Experiments with soils such as the Oakley sand demonstrated that even though a tight surface layer and a limiting zone appear any given depth of a coarse soil is not as effective as the same depth of finer soils in removing coliform organisms from a percolating liquid. Under test conditions such as those from which the data for Figure 10 were obtained, the Oakley sand contained only 6.9×10^5 organisms per gram of soil at 65 cm depth, in contrast with 2.84×10^6 in the finer Hanford Loam, while the effluent at that depth carried 6×10^3 organisms per 100 ml as compared with but 230 per 100 ml for the Hanford soil. A similar contrast in bacterial removal was noted between the relatively fine soil at Whittier and the coarse material at Azusa. These and other observations support the general conclusion that the removal of bacteria from liquid percolating through a given depth of soil is inversely proportional to some function of the particle size of the soil.

In the lysimeter studies removal of bacteria was generally high in Hesperia, Columbia, Hanford, and Yolo sandy loam. Less than five percent of effluent samples from a 3-foot depth of the first two of these soils showed coliform concentrations in excess of 1000 per 100 ml when the applied sewage carried coliform concentrations varying from 2.4×10^6 to 11×10^6 per 100 ml. The Hanford soil produced some 23 percent of samples with more than 1000 coliform organisms per 100 ml. Coarser soils such as Yolo and Oakley were poorer in their capacity to remove bacteria from applied sewage. A striking example of the relative effect of coarse and fine soils is illustrated in Table VII which shows greater coliform counts at two feet below the surface of Basin A than at one foot. At the close of the experiment a cross sectional excavation of the basin in the vicinity of the sampling pan located at the two foot depth revealed the existence of a sand tube extending to the surface. In this case two feet of sand in a small intrusion permitted the passage of from 20 to 200 times as many bacteria as did one foot of Hanford loam. The buildup of a limiting zone in the form of a surface mat which rapidly sealed the more pervious tube, probably accounts for the fact that few bacteria reached the two foot level when primary effluent was applied than when a much less polluted final effluent was used.

None of the five soils observed produced effluents which, after movement through a 3-foot depth, could consistently qualify under the U.S.P.H.S. standards. There was no evidence that coliform organisms travel downward more readily during the initial stages of spreading than during later stages. Of particular interest was a lack of correlation between infiltration rates of various soils and the corresponding degree of bacterial removal.

The results of experiments with fine soils spread with sewage at Whittier, Lodi, and in lysimeters studies seem to substantiate the 5-foot distance considered reasonably safe by Kligler (55) and Caldwell (56), as well as the generally accepted conclusion that the addition of waste water to the ground water by spreading may be bacterially safe. In view of the experience with coarser soil in Lysimeter studies, at Azusa, and at Manhattan Beach it does not seem practical to write any general specification of the minimum distance from the ground surface to the water table which should be maintained in order to prevent coliform bacteria from reaching the ground water along with percolating waste water. Because of the possibility of rodent holes, root holes and other pervious paths it seems best to assume that in practical ground water recharge by surface spreading, some coliform organisms will reach the ground water with percolating sewage in many cases unless, perhaps, the soil stratum above the ground water is very thick. That this does not in itself constitute a serious danger to the public health is best shown by experiments in the travel of pollution with ground water movement.

Travel of Bacteria With Ground Water. In the Richmond recharge studies (4) observations of the extent of travel of bacteria associated with water degraded to 6, 10, 20, and 27 percent sewage were made at recharge rates of 3.1, 3.8, 8.4 and 14.2 gallons per minute per foot of aquifer. Coliform organisms were used as the principal indicator of bacterial pollution although on occasion Streptococcus fecalis was also used as an indicator organism because its size dissimilarity to coliforms led to the suggestion that it might move at a rate and through a distance intermediate between coliforms organisms and dissolved matter. Plate counts were used to observe the travel of bacteria in general and identify the existence of a moving substrate capable of sustaining organisms existing in sampling wells. The rate of travel of bacteria was compared with that of the transporting water as shown by fluorescein and other tracers.

Comparative rates of travel of injected water and coliform organisms are shown in Table VIII for a series of experiments in which sewage was injected at a rate of 8.4 gpm/ft of aquifer for a total of 46 days after the aquifer had previously been recharged with fresh water and tracer dye only.

From a study of Table VIII it is evident that bacteria to a significant degree moved less rapidly than fluorescein, and hence move more slowly than the transporting water. Later experiments showed this to be true of particulate matter in general in comparison with dissolved materials. It was also evident that recharged water, and with it chemicals and bacteria, move outward from the recharge well along paths of lowest permeability at rates much greater than that of the mass of injected water, represented theoretically by an expanding cylinder of recharged water which displaces the normal ground water in the pores of the aquifer. This not unexpected fact made it necessary completely to fill the aquifer to any sampling point in order to obtain maximum values of Most Probable Number (MPN) of coliform organisms from which to evaluate the time-distance change in bacterial densities. Both the time of arrival of first pollution and the maximum density of coliform organisms are of importance. However, from a public health standpoint the fact of arrival of bacterial pollution at any distance from a point of injection may be considerably more important than any subsequent increase in intensity of pollution.

Table VIII also shows that the rate of movement of both bacteria and tracers was by far the greatest in the direction (south) of normal ground water flow. The fact that coliform organisms reached a point 100 feet south of the recharge well in 33 hours, but failed to reach a distance of 200 feet in 46 days is extremely important. A uniformly expanding cylinder of water would have acquired a radius of 200 feet in approximately 32 days under the rate of recharge used in the experiment. Since other data in Table VIII show a heavy distortion of the recharged water toward the south, it is evident that injected water filled the aquifer at to the 200-foot observation wells for a period considerably in excess of 16 days. Obviously die-away of bacteria cannot account for the failure of coliforms to extend 200 feet, either by the easy paths of early travel, or with the mass of moving water which arrived later.

Daily samples taken during a 38-day period of continuous injection of a mixture of 90 percent water and 10 percent primary settled sewage showed that bacterial pollution of the observation wells was greatest near the beginning of the period of recharge but subsequently decreased. When correlated with the rate of advance of the mass front of injected water, and with the build-up of a filter mat at the aquifer face, as shown by injection pressures, these phenomena are readily explainable. The first coliform concentrations represent pollution which has arrived at any observation point by the least resistant route;

TABLE VIII

Rates of Travel of Coliform Organisms and Injected Water

Distance From Recharge Well	Time of Arrival of First Injected Water, as shown by Fluorescein (hours)		Time of Arrival of First Coliform Organisms (hours)		Calculated Theoretical Time of Arrival of Mass of Injected Water (hours)
(feet)	Avg. all Directions	Max. any Direction[a]	Avg. all Directions	Max. any Direction[a]	
10	0.64	0.2	1.73	0.33	2
25	4.30	0.6	6.78[b]	0.33	12
50	12.0[c]	1.4	17.55[d]	2.1	48
100	—	15.0[e]		33.0	187
200's	—	—	—[f]	—[f]	

a Direction of normal ground water movement (S)
b Did not reach 25' west in 24 days
c No data at 50' North
d Did not reach 50' North or West in 24 days
e Reached 100' South only
f Did not reach 200' South in 46 days

the maximum concentrations represent the arrival of the mass front of injected water; and the subsequent decrease results from a combination of bacterial die-away and a reduction in the number of organisms passing through the developing filter mat of organic solids at the aquifer face. Experience in the Richmond studies showed that maximum coliform concentrations occurred on the third day after the beginning of sewage injection at 84 gal per min per foot of aquifer, and at proportional times when other injection rates were used.

Table IX presents the MPN of coliforms at various distances from the recharge well on the 3rd, 12th, and 32nd day of the previously mentioned 38-day period of recharge with sewage containing 2.4×10^6 coliform organisms per 100 ml. It is notable that the most distant wells showing pollution at any time during the recharge period were 100 feet to the south of the point of injection and 63 feet in other directions. Moreover, the small number of organisms at the most distant points showing pollution indicate that bacterial travel in the aquifer beyond 100 feet is negligible, and the change in pollutional intensity with time shows that prolonged recharge does not cause bacteria to extend beyond their initial distance of travel.

Subsequent experiments were conducted with a mixture of 27 percent sewage and 73 percent water, having a coliform concentration of 4.7×10^6 organisms per 100 ml. No increase in the distance of travel occurred after the 3rd day; no well more distant than 63 feet from the recharge well showed coliform contamination; and no increase in the intensity of pollution at the maximum distance of travel appeared. Numerous studies with 20 percent sewage at various recharge rates during a period of more than eleven months gave similar results.

Observation of the numbers of <u>Streptococcus fecalis</u> showed no difference in the observed distance of travel of that organisms and of coliforms. As in the case of coliforms, the numbers increased at first, then regressed, but because of the much smaller initial numbers of <u>S. fecalis</u> present it was concluded that the organisms was less desirable than the coliform group as an indicator of pollution.

Plate counts of organisms indicated that bacteria in general are removed by the aquifer material in the same manner as are coliforms, possibly to a greater degree in relation to distance from the point of injection. When the cap was left off an observation well located 463 feet

TABLE IX

MPN of Coliform Organisms in Observation Wells During Continuous Recharge with an Average of 2.4×10^6 Organisms per 100 ml

Distance From Recharge Well	MPN, 3rd Day	MPN, 12th Day	MPN, 32nd Day
13 Feet N	240	240,000	230
28 '' N	2400	240	5
47 '' N	240	38	5
63 '' N	23	8.8	None
88 '' N	None	None	None
138 '' N	—	None	None
39 '' NE	2400	240	8.8
45 '' NE	None	8.8	None
63 '' NE	None	38	None
106 '' NE	None	None	None
39 '' NW	2400	240	2300
45 '' NW	240	None	5
63 '' NW	None	2.2	8.8
13 '' E	24,000	24,000	8.8
50 '' E	240	5.0	None
13 '' W	23	None	2300
50 '' W	23	>240	2.2
13 '' S	95	2400	230
63 '' S	None	None	9.4
100 '' S	23	5.0	None
188 '' S	None	None	None
192 '' S	None	None	None

from the recharge well, however, high plate counts (3000 per ml) were obtained. This demonstrated clearly that nutrient materials dissolved in the water may travel readily with the ground water and serve as a substrate for general types of saprophytic organisms already present in a nearby well.

One of the most important findings in the Richmond studies is that the rate of bacterial removal with distance is a function of the aquifer characteristic known as filterability; and that for any degree of filterability it depends upon distance only and not upon the rate of recharge. On this point it was observed that the rate of decrease in numbers of organisms per foot of distance was little affected by a ten-fold change in water velocity.

On the basis of results of the Richmond studies it may be concluded that the reclamation of sewage plant effluents by recharging them directly into the ground water carried in an aquifer such as the one investigated would not be limited by public health concern over bacterial contamination, although dissolved nutrients might contribute to the growth of general saprophytic bacteria in wells near to the point of recharge.

Experiments with spreading of sewage showed conclusively that an organic mat of increasing ability to filter out bacteria forms at the soil surface and accounts for an important reduction in bacterial numbers in infiltrating waters. A second major reduction in bacteria occurs as percolating waters enter a characteristic limiting zone within the soil. Lysimeter studies showed, however, that those organisms which passed through the limiting zone continued to travel the remaining length of the three-foot columns used in the experiments, with only a relatively small reduction in numbers. Thus it seems possible that in a water reclamation project involving spreading on coarse soils, appreciable numbers of organisms might find their way to a high ground water table unaccompanied by suspended organic matter capable of forming an organic mat. In a recharge situation of such nature, dilution would reduce the clogging potential of any dissolved organic matter and thus, it has been argued, conditions most favorable for pollution travel would be developed.

Presuming that a spreading operation would not be undertaken on a thin stratum of coarse soil overlying fissured strata, there are several reasons why the foregoing circumstance should not be a serious matter. First, the drastic reduction in organisms occurring during infiltration would result in a degree of contamination much less severe than that imposed by the direct recharge experiments found to be safe at Richmond. Next, there would be a tendency for dilution, inasmuch as percolating waters would be less likely than injected water to displace all other water in the aquifer in the area recharged. And finally, since the initial movement of pollution in the Richmond experiments was essentially unhampered by the suspended solids present in the recharge water, it should be analogous to the movement of percolated sewage under similarly steep gradients. Since no such gradients can be imposed by percolating water, the limited initial travel of bacteria in the Richmond studies may be interpreted as evidence of the small importance of sewage spreading as a public health hazard under practical controlled conditions.

From available experimental data it is concluded that engineered reclamation of sewage and similar waters containing organic wastes is not primarily a public health problem as far as bacterial pollution of ground waters is concerned.

Experimental Studies of the Travel of Chemicals

As previously noted, experimental data on the rate and extent of travel of chemical pollution is somewhat limited. Gross observations or findings incidental to bacterial studies are generally reported in the literature. These reports show that chemicals may travel such great distances that in the experiments at Whittier, Azusa, Lodi and Richmond it was not considered feasible to attempt to define the limits of travel of chemicals with transporting water. Consequently, only a small amount of significant data were obtained, except on a few compounds associated with biological decomposition of organic matter, although hundreds of chemical analyses were performed.

In the Lodi studies it was found that calcium, magnesium, sodium, and chlorides remained relatively constant through the 13 feet of soil depth observed. Sulfates, bicarbonates, and nitrates increased very markedly. Phosphorous disappeared within the first foot and ammonia within the first four feet of soil, while potassium decreased by approximately 50 percent below seven feet.

The lysimeter studies afforded a better opportunity to observe in detail the behavior of several soils under spreading with both water and sewage. Samples of the soils after prolonged application of either liquid showed increases in sodium, potassium, and ammonium ions and reductions in calcium and magnesium. These changes were common to all soils except the Hanford fine sandy loam (Lodi), and were more pronounced with sewage than with water spreading. The clay content of all soils investigated was, however, generally low (below 10 percent) and ion exchange was therefore not sufficient to reduce infiltration rates by clay dispersion.

An equilibrium between influent and effluent calcium was approached in Yolo and Oakley soils in from 8 to 17 weeks, but both of these soils showed a tendency to give off more magnesium than was applied throughout a spreading period of 23 weeks. Effluents from the finer textured soils, Hanford, Hesperia, and Columbia showed an increase in calcium for about two weeks, then a gradual decline. In later weeks of sewage spreading the magnesium content of the effluent from these soils also approximated that of the influent. Sodium and potassium balances, however, indicated that ion exchange was fairly well completed by the end of 15 weeks of spreading.

During this 15-week period, of course, ion exchange between soil and percolating liquid had the effect of reducing the ratio of monovalent to total cations in the liquid. However, throughout the sewage spreading experiments the ratio for the effluents of all lysimeter soils was greater than 50 percent, the usual maximum for acceptable agricultural waters.

In the Richmond experiments with direct ground water recharge the recharge well was effectively clogged by introducing a concentrated solution of sodium chloride as a tracer. In other experiments ion exchange was evidenced, although no observable clogging occurred, by the appearance of greater concentrations of calcium and magnesium in the observation wells when moderate amounts of sodium appeared in the recharge water. This, of course, had the effect of increasing the hardness of the ground water.

Chemical constituents such as ammonia, nitrites, nitrates, phosphates, sulfates, bicarbonates, and oxygen demand, which may be altered in the biochemistry of organic solids showed the greatest changes in experimental studies.

In lysimeter experiments phosphates showed less inclination to disappear than observed at Lodi but in all cases phosphates were reduced during percolation of sewage through 3-feet of soil. During direct recharge in the Richmond studies it was noted that phosphate reduction occurred between the recharge well and the nearest observation well but that thereafter only a slight decline, if any, occurred within the limits of the well field. This was interpreted as meaning that, to a significant degree, phosphates were associated with the suspended solids removed in the clogging zone adjacent to the recharge well.

Sulfates declined with time after the start of spreading of sewage on soils in lysimeters. At the same time bicarbonates increased and nitrates disappeared. This indicated that anaerobic conditions existed in at least some zones of the soil. The trend of effluent BOD also supported this conclusion. Applied sewage having a BOD of 100 ppm yielded effluents with a demand of less than 5 ppm at first. At the end of 4 weeks this amount had risen to 26 ppm, and later to even greater amounts, indicating the decreasing availability of oxygen.

In the Lodi studies aerobic conditions prevailed in the soil with the result that a favorable environment for oxidative reactions was provided. Effluent Dissolved Oxygen at 13 feet in Basins A, B, C, D, (Table III) were of the order of 6 ppm. Sulfates, nitrates, and bicarbonate increased with depth, as previously noted, and remained relatively constant in amounts throughout the period of spreading. In contrast to the lysimeter results the effluent BOD was never greater than 5 ppm. The applied BOD, however, was but 10 to 15 ppm.

Experiments at Azusa and Whittier substantiated the lysimeter and Lodi results. An applied BOD of about 7 ppm was reduced to less than 0.5 ppm in seven feet of percolation at Whittier under aerobic conditions. Loadings of 100 ppm at Azusa, however, resulted in anaerobic conditions and a BOD reduction of about 75 percent in seven feet as compared to some 93 percent at Whittier.

Direct recharge of sewage effluents having a BOD of some 8 ppm produced no serious problems of water quality. Results indicated that much of the BOD was represented by dissolved organic matter but a rapid reduction took place near to the recharge well, the decrease in BOD with distance paralleling the decrease in concentration of coliform organisms. There was a definite tendency for nitrates to decrease and nitrites to increase near the recharge well and for the reverse to occur at greater distances. Correlated with BOD observations this is evidence of denitrification in and near the clogging zone.

As might be expected from experience with natural waters, calcium, magnesium, sodium, potassium, chloride, nitrate, sulfate, phosphate and bicarbonate ions moved freely with the ground water and no tendency for removal could be observed within the limits of the well field. The experiment was not concerned with other ions which might occur in industrial wastes.

Implications of Experimental Studies. The implications of the results of spreading studies are, of course, that in the interest of highest quality of ground water, spreading should be conducted under conditions which maintain an aerobic environment. It can be demonstrated, however, as a result of the direct recharge studies, that the rate of aquifer clogging rather than the bacterial quality of water governs the nature of waste water which can be effectively recharged. This means that practical ground water recharge undertakings are likely to be concerned with secondary sewage effluents and hence the danger of anaerobic conditions developing in the soil is not great.

When the origin and nature of waste waters are considered there seems no reason to expect that the reclamation of domestic sewage, food processing waste waters, and similar wastes should produce a public health problem or bring about any important long term deterioration of water quality. Natural recharge water normally consists of meteorlogical waters carrying little chemical constituents other than dissolved carbon dioxide and other gases, mostly of atmospheric origin. These pick up earth minerals and when pumped from the ground for use in public water supply generally contain soluble minerals characteristic of the underground formations through which they have passed and from which they are pumped. Cation equilibrium will have become established underground and since ground waters are normally developed for consumptive use in the immediate vicinity, no difficulty would be expected from pumping the water back underground unless the consumptive use has appreciably altered its chemical characteristics. Generally the total ion content of sewage is no greater than normally found in ground water, hence a deterioration in water quality by a gross increase in ions would not result.

Surface waters are often transported long distances and might, therefore, differ materially from both the surface and ground waters at the point of consumptive use, but this difference is either one of degree only or in the amount of organic matter carried. In general, surface waters are intermediate between meteorological and ground waters in chemical quality and present no problems of water quality unless greatly modified by consumptive use.

Changes in water quality by use differs, of course, with the nature of the usage. Water softened prior to domestic consumption may possess sufficient sodium to bring about appreciable ion exchange underground. This may result in dispersion of clays and clog the soil or an aquifer in such a manner as to interfere with successful ground water recharge. Where the recharge water is principally sewage little change in water quality would be expected, except in the concentrations of compounds of nitrogen, sulphur, and perhaps phosphorous, and in dissolved oxygen and oxygen demand, unless the sewage contains objectionable amounts of any of several industrial wastes. It is well known that phenols, metal plating wastes, cyanides, oils, synthetic rubber wastes, and a variety of other industrial waste waters may make water unpotable or even toxic. Underground travel of such materials has been observed to cover many miles, and it seems probable that many industrial waste waters are unfit for use in ground water recharge operations and might have to be excluded from sewage to be reclaimed.

From the results of experimental data and from such field experience as has been reported it may therefore be concluded that dissolved chemicals in general can be expected to travel long distances. Unstable dissolved organic matter subject to bacterial decomposition, however, will undergo chemical changes, and some removal by bio-precipitation is likely to occur. In the case of certain industrial wastes there is likely to be some removal by adsorption of ions not characteristically derived from normal geological strata. Some evidence of adsorption of fluorescein used in tracer studies, for instance, developed during the recharge experiments. Metal ions may to some extent be removed from industrial wastes by ion exchange, but the variety of such wastes is so great that it is difficult to make any general statement of the suitability of industrial process waters for use in ground water recharge except, as previously noted, to anticipate the unsuitability of wastes containing chemicals which are toxic, or noxious for other reasons.

Presuming that sewage free of serious amounts of unsuitable industrial wastes most likely to yield important amounts of reclaimable water, and that for operational reasons a final treatment plant effluent will be used, the problems of chemical travel do not seem to be too serious. Some concern has been expressed over the build-up of dissolved solids if water is pumped from the ground, used in domestic and commercial supplies, and returned to the ground water. Obviously a closed system would eventually lead to a ground water of seriously lowered chemical quality, just as the total salt content builds up in a surface lake subjected to intensive use and reuse. Granting that much remains to be learned about the long range change in quality of a ground water repeatedly recharged with degraded waters, there is nevertheless a good probability that the decline would not be catastrophic. More likely a normal underground water would never reach the condition already tolerated without harmful effects in some areas where ground waters contain large amounts of dissolved solids. It might develop, however, that where local ground waters are already marginal in quality, ground water recharge is not the method of water reclamation to be recommended. As discussed in a subsequent section of this report, some other method might be more appropriate. Some areas having poor quality local ground waters find it possible to import surface waters of much higher quality. In such cases it is conceivable that sewage reclamation by recharge might serve to upgrade the local ground water.

As observed in the lysimeter studies, sewage reclamation by spreading for the purpose of ground water recharge might produce a ground water with a ratio of monovalent to total cations unfavorable for agricultural use. This is probably not a serious matter because water entering the ground water by percolation is unlikely to displace aquifer water so completely that an undiluted mass of reclaimed water moves through the aquifer. Therefore, dilution seems likely to exercise a corrective effect. In the case of direct recharge of sewage into an aquifer, ion exchange is not expected to be as serious as in the case of spreading, unless the aquifer carries an unusual amount of clay.

Some concern has been expressed over the health and water quality hazards which might develop as a result of the widespread use of new products which find their way into sewage and thence into the ground water by way of reclaimed sewage. Detergents and radioactive wastes are two examples which have sometimes been cited as materials that might possibly render impractical and otherwise satisfactory water reclamation project. There are a number of reasons why neither of these wastes will destroy the reclaimability of domestic sewage. First, it has not been demonstrated that detergents render a water unfit for further use. Should such an eventuality develop either in the case of present or future products of this nature, treatment processes which precede final water reclamation must be designed to correct the situation since it would be impossible to get rid of water in any manner whatsoever if its quality is impaired beyond recall. Conversely, any material capable of polluting water beyond salvage must of necessity be excluded from sewage in important amounts. Radioactive wastes fall into this latter category, hence they simply cannot dispose of by promiscuous discharge to sewers or streams as has been the case with less objectionable industrial wastes. Studies are currently under way to determine effective means of radioactive waste disposal into soils or into ocean depths.

In the foregoing discussion no mention is made of the water quality or public health aspects of ground water recharge by excess surface waters. The nature of these waters is such that bacterial quality causes no concern, and their chemical quality is essentially that of meteorological waters. The effect of recharging with flood waters would therefore be that of chemical upgrading rather than degrading the ground water.

The general conclusion may be drawn that in a properly engineered and operated ground water recharge project, suitably located, and involving water from which certain types of industrial wastes have been excluded, the public health should not be endangered nor the quality of ground water degraded to an unacceptable degree. In this connection it seems both desirable and inevitable that as the population grows and re-use of water becomes increasingly necessary, the criteria by which water quality is judged acceptable shall have to be re-examined. Medical research may well show present standards to be excessively conservative in terms of human tolerance, and engineers may find it necessary to provide closer controls and better operational procedures in order that present factors of safety may be reduced. It may well be that in the future it will be as impossible to operate with the water quality standards of today as would be aeroplane of today if built with the factor of safety of yesterday's highway bridge.

ENGINEERING AND ECONOMIC ASPECTS OF GROUND WATER RECHARGE

Status of Recharge Problems

The engineering and economic problems associated with waste water reclamation by ground water recharge have been defined largely by experiments conducted primarily to explore the dangers of pollution travel. Although the results have been significant they are of necessity in scale with the limited effort which has been directed toward reclamation of wasts as a result of our historic lack of any need for planned conservation.

It has been shown with reasonable certainty that under suitable geological conditions ground water recharge should not endanger the public health through bacterial contamination, and that a proper selection of wastes to be recharged should furnish ample protection against toxic chemicals and against any serious long range deterioration of water quality. Furthermore, public resistance to waste water reclamation by ground water recharge does not seem to be a problem. Perhaps the ancient faith of men in the inherent purity of cool spring and well waters may contribute to a general failure of people to associate ground water with its origins. A more probable explanation in California and the southwest is an intelligent understanding on the part of citizens of the west's need for water, for in no other section of the United States is the importance of water so obvious to even the most casual observer. In almost every one of the arid western states industry and agriculture in cooperation with towns and cities are attempting to reclaim or re-use waste waters. In many cases the public health reliability of the measures adopted is undoubtedly questionable, while the methods are often trial and error procedures directed by necessity rather than well planned and engineered attempts at water reclamation. Most of them deal with simple surface ponding, land irrigation, or re-processing above ground, rather than with more complicated procedures requiring solutions to new engineering problems.

Experimental Findings

One of the most significant findings of the experimental studies was that no special treatment processes need be applied to a sewage plant effluent before spreading it on the surface or injecting it underground. Previous beliefs to the contrary were based upon the presumed danger of pollution travel or, in the case of direct recharge, on the assumption that well clogging is so irretrivable that only a highly clarified water can be injected. De-aeration, formerly reported as essential, was also found to be unnecessary. In the spreading studies at Lodi, and in the lysimeter experiments, it was found that a primary effluent could be satisfactorily spread without producing odors in the vicinity of the operation as unsatisfactory conditions underground. In some cases, however, and notably in the Azusa studies, the desirability of using a final effluent in order to maintain aerobic conditions underground was evident. In direct recharge studies a diluted primary effluent was used for convenience but the expectation was that a final effluent would be used in the practical case because of the obvious impracticality of supplying fresh water merely to dilute sewage for recharge. Recharge with flood waters produced no problem except where silting tended to clog the surface of the spreading basin. From an engineering viewpoint the important fact is that all necessary pretreatment can be accomplished by well established treatment processes normally in use in waste treatment plants, or in desilting basins. Thus no unresolved engineering problems are imposed in preparing waste waters for reclamation by ground water recharge.

The Richmond studies showed that direct recharge can be accomplished at pressures much lower than previously thought to be necessary on the basis of oil field experience with deep strata of a low degree of perviousness. Rates of injection equal to the best reported for ground water recharge with clear water were achieved with pressures about equal to the drawdown head involved in pumping water from the well at a similar rate. This means that under conditions as favorable as those observed in the experiments, the cost of recharge and of well redevelopment is governed by the cost of installing and operating normal water handling equipment. A similar lack of need for special equipment was observed in the case of the recharge well. Here a common type of gravel packed well of readily estimable cost proved satisfactory.

In the Richmond experiments is was necessary to redevelop the recharge well every seven or eight days when sewage containing approximately 8 ppm of suspended raw sewage solids and a similar concentration of BOD was injected at a rate of 8.4 gpm per foot of aquifer having a permeability of about 1900 gallons per square foot per day. In this case the maximum permissible recharge pressure was taken as 60 to 65 feet above the normal ground water level. A maximum of four percent of the injected water was discharged during re-development. The recharge rate was one-half the safe yield of the well and redevelopment was accomplished at twice the recharge rate.

In a general case the rate of injection would depend upon the permeability of the aquifer. The length of time between redevelopments would in turn depend upon the recharge rate, the amount of solids introduced per unit of recharge water, the permissible loss of head through the filter mat (well head pressure), and the area of exposed aquifer face (diameter of gravel pack). One of the principal advantages of a gravel pack surrounding the recharge well screen is that it provides a greater effective aquifer face. By gradation of particle size it also makes for a filter mat of greater permeability for any given amount of accumulated solids than would occur at a more sharply defined aquifer face. The amount of water returned to the surface during redevelopment would, of course, depend upon the length of pumping time required for redevelopment, and would have to be worked out in each individual case.

Using values presented in the Pollution Travel Report (4) as a basis for judgement, the rate of clogging of an aquifer of known permeability when recharged with a sewage of known suspended solids content could probably be estimated with sufficient accuracy for preliminary cost estimates. Should it be desired to remove suspended solids above ground by filtration, thus obviating the need for recharge well redevelopment, the cost could readily be estimated from engineering experience in water filtration.

In the Richmond experiments the redevelopment water was discharged to a sewer. A practical recharge operation would presumably require settling of the well discharge for reinjection underground. Field observations indicated that such a treatment could be readily accomplished. Organic matter brought up during redevelopment was flocculent in nature and was easily skimmed off after a very short period of quiescence. Settleable solids likewise separated out in a few minutes. With a number of recharge wells on a staggered schedule of redevelopment the installation for reclaiming water discharged during redevelopment would not be extensive.

The cost of any project involving ground water recharge should include some preliminary exploratory work. This, however, should not prove to be out of scale with similar studies required on most other important engineering work. Test wells would presumably be necessary to obtain a knowledge of the aquifer - its permeability, thickness, and amount of overburden. Similar test holes would reveal the soil conditions and nature of the strata underlying a proposed spreading operation. Many agricultural soils are shallow and underlain by limiting zones between the soil and any strata which might take and important amount of water. Test holes, therefore, seem necessary in locating and estimating any ground water recharge project.

Practical injection projects involving sewage should include provisions for monitoring of the recharged water. On the basis of the Richmond studies wells at 50 and possibly 150 or 200 feet down the stratum from the recharge well should be provided for periodic sampling, although there need not be two observation wells for every recharge well used in the project.

The field performance of a soil under spreading can be determined by short term lysimeter tests after field borings have established the suitability of a general site in terms of soil thickness and underlying pervious strata. Provision for such a preliminary study should be included in an estimate of cost unless the behavior of the soil under field conditions is known.

Type and Location of a Recharge Project

The method of recharge best adapted to any ground water recharge project depends upon a number of factors which can be evaluated only on the basis of specific field data. Geographic, topographic, geologic, and economic considerations enter into the final engineering decision as to whether over-irrigation, surface ponds, or direct injection is the most suitable method.

Normal irrigation is one of the most common methods of waste water utilization. Over-irrigation as a device for ground water recharge, however, may be of limited possibilities, because the circumstance in which agricultural land overlays strata that are continuously pervious down to an aquifer is not exceedingly common. Alluvial fans, and sedimentary soils may be continuous to water bearing strata, while residual soils and soils of other origins may be separated from the ground water by one or more limiting zones of relatively impervious material. The capacity of the soil to receive water is then limited to the volume of its own pore space above the limiting zone.

Over-irrigation also poses another problem which limits its possibilities even on suitable agricultural soils. That is the matter of water rights. An agriculturist who has rights to present irrigation water under circumstances in which the cost of water is governed by known legal considerations, might be understandably reluctant to risk the loss of those water rights by accepting municipally owned wastes, the value and availability of which might vary with local administrative changes.

The same soil conditions which limit ground water recharge by over-irrigation may also place limitations on surface spreading or govern the choice of location of such a reclamation project. Should it be necessary to break through limiting strata in order to provide pervious paths for surface waters it is probable that direct recharge would be more economical than spreading on the same site. On the other hand, a spreading operation might be located on soil overlying fissured strata totally unsuitable for direct recharging. In such a case, however, consideration should be given to the relationship between permissible pollution of ground water and the degree of pretreatment required. Unless the surface soil overlying fissured strata is quite thick, it is well to assume that some coliform organisms will be introduced into the ground water and to plan accordingly.

The distance from soil surface to the water table which might effect any prescribed degree of bacterial removal is problematical even in the case of a soil type of known general characteristics. Rodent holes, root channels, and other pervious paths may lead to appreciable depths and provide easy routes for pollution travel. The seriousness of any probable intensity of pollution must be judged in each individual case. Ground water contamination might be of little concern to agriculture while of greater concern to domestic users. On the other hand, tastes, odors, and undesirable chemical characteristics are much more likely to render recharged water unsatisfactory than are bacteria, and somewhat more difficult to control. Where spreading grounds overlie sand aquifers the possibility of easy routes of pollution travel through overlying soil is of little concern, as the movement of bacteria which reach the ground water is not of serious import. One of the most serious problems of location of recharge operations, and one which may well be economically insurmountable at any given time, is the fact that in many areas the proper place for recharging an aquifer is at its higher elevations while by the very nature of sewer systems the reclaimable waste is concentrated at a low elevation. This is particularly important in coastal cities, and may be more serious to spreading operations than to direct recharge projects. The ideal situation, of course, would be one in which recharge can be accomplished at the point of occurrence of a waste water, while transportation to the point of use occurs by underground travel of ground water.

Available land areas for spreading, which are both technically suitable and environmentally acceptable, may be a governing factor in deciding whether ground water recharge is feasible or in choosing the type of operation. In general the direct recharge method recommends itself by reason of the cleanness of the recharge operation, its adoptability to any topography, and the limited surface area required. On the other hand geological considerations might preclude its use altogether in an area where spreading is feasible. In addition, the installation and power requirements of direct recharge might exceed in cost those for a spreading operation.

For obvious reasons it would be undesirable for producing wells to be located too close to the points of recharge. As a result the public agency responsible for water reclamation would find it necessary either to own or control land in the vicinity of the recharge operation. Such a requirement should be considered in an appraisal of the land requirements for a reclamation project.

In the case of flood water where large volumes of available water occur seasonally direct injection would not seem competative with spreading as a method of reclamation. Land area requirements are difficult of estimate in the absence of specific data. Experience in the studies described in this report, however, indicates that about one cubic foot of water per square foot per day might be expected to infiltrate soils as favorable as those tested. On this basis some three acres would be required per million gallons of sewage. At 3.5 to 4 gallons per minute per foot of aquifer, two wells penetrating 100 feet of aquifer would be required for a similar recharge. Depending upon many factors which can not be evaluated in a hypothetical case, either one of these might prove to be the cheaper in a situation where both possibilities exist.

No single general criterion can be established for determining the engineering economy of a spreading or direct recharge operation. Engineering problems must be solved to fit individual circumstances. The important fact is that the solutions themselves involve no considerations unusual in present engineering practice. Studies of the economic feasibility under certain practical conditions in California are in progress.

Value of Reclaimed Water

To some degree the economics of water reclamation depends upon the value of waters available for recharge. In the case of excess flood waters the cost of reclamation may be simply weighed against the known market value of irrigation water in the area, or against the profit to be made by applying it to land. Essentially publicly owned water is being reclaimed at public expense, although the legal manner in which the public is repaid the cost of reclamation is deeply involved in the laws of water rights and taxation.

In the case of waste water from domestic and industrial use, however, thinking regarding the value of reclaimed or reclaimable water is by no means crystallized. One of the most interesting differences of opinion which has developed in recent years concerns the value of treated sewage. The practice of sewage treatment has developed in a curious fashion from the standpoint of water quality. Traditionally sewage has been a worthless and objectionable material to be disposed of in the cheapest and most convenient manner. This meant dumping it into the nearest watercourse or tidal estuary without treatment. At first this created nothing worse than a nuisance to a few riparian owners, but as cities and industries grew and an ever increasing usage of available water became necessary, the need for protecting public health, aquatic life, shipping, and recreational facilities made sewage treatment inescapable. Step by step, cities resorted to primary treatment, to secondary treatment, and finally to effluent chlorination. Each of these steps upgraded the quality of the waste water but the fact was little recognized because in the public concept sewage still remained a worthless material, to be thrown away as always.

As a consequence of this historic attitude toward waste waters many of those who first thought seriously of reclaiming waste waters, whether by ground water recharge or by irrigation, thought of sewage plant effluents as having no value. Municipal officials, however, suddenly realized that in treating sewage they had unconsciously upgraded its quality and hence presumably increased its value. The extent to which that value has been increased, however, is at best debatable. From one point of view it would seem that reclaimed water should be worth exactly the same as any other water equally suitable for a given purpose. Psychologically, however, this is not the case as users invariably prefer first use water to re-use water at the same price. This consideration suggests a concept of the value of water based upon the degree of quality degradation resulting from prior use. Obviously the great variety of natural water quality, the many degrees of degradation by use, and the quality requirements of different users introduces such infinite variability as to render absurd any idea of value in terms of quality, except in the case of the comparative cost of treating two waters to make them acceptable for one particular use.

Much of the foregoing thinking concerns the value of waste waters reclaimed above ground for use of industry or for crop irrigation. Obviously a city is justified in regaining such of its sewage treatment costs as possible and in selling effluent at a price attractive to private users. Where such scale is not possible, however, a reclamation by ground water recharge is practical for public benefit it is difficult to see how use of water by the citizens of a community can be interpreted as acquiring ownership to the degree that the general public must buy it back before further use. This poses legal questions beyond the realm of the engineering and general economic aspects of water reclamation. Problems of operation rather than considerations of public health govern the practical aspects of water reclamation by ground water recharge. It now seems that the feasibility of water reclamation by ground water recharge may largely depend upon legal arrangements.

The general conclusion from laboratory and field studies of control of sea water intrusion is that it is possible to hold back intruding sea water by recharge mounds, pumping troughs and cut-off walls. However, is such methods are used merely to postpone the date when over-exploration of a ground water basin must cease they may be of doubtful values. When used to protect existing aquifers temporarily while the results of previous over-exploration are remedied, they may be justified as expensive but necessary devices to compensate for past folly.

SOME OTHER WATER RECLAMATION POSSIBILITIES

Although the body of this report has been primarily concerned with the reclamation of waste waters by ground water recharge significant studies have been made of other procedures which might have a similar effect in increasing the amount of useful water available for consumptive use. In general, these measures deal with protection of the quality of existing waters, direct re-use of waste waters, and reclamation of saline or brackish waters.

Protection of Existing Ground Waters

Significant studies which bear upon increasing the amount of available ground water by protecting its present quality have been sponsored by public agencies in California. One of these, sponsored by the California State Water Resources Board, was a laboratory (5) and field study (87) of the use of recharged waste water to create an underground fresh water mound capable of halting the advance of sea water into important coastal aquifers currently under overdraft conditions. Obviously such a measure would not add greatly to the amount of water available for beneficial use. Rather its effect is to give the water consuming community time to make arrangements for other sources of water, and to protect a vast underground reservoir and transportation medium from ruin by sea water until such time as the inland water table can be restored to a suitable elevation to protect the aquifer without artificial recharge.

The principles of sea water intrusion and its control have been under consideration for about 65 years. In 1889 Ghyben (88) discovered a principle which enabled him to state with certainty that sea water intrusion would take place when certain relationship existed between fresh water in an aquifer and sea water at the aquifer outcrop. Prior to that time it had been debatable among engineers (89) whether sea water would infiltrate an aquifer in which the ground water table had been reduced below sea level. In 1901, however, Herzberg (90) demonstrated by test borings that the Ghyben principle held, and successfully applied it to the water supply problem along the North Sea. During the next four years various observers (91) (92) (93) (94) in the low countries of northern Europe, although sometimes in disagreement, found the Ghyben-Herzberg principle to hold in specific instances of sea water intrusion. Later reliable in observations of sea water intrusion in Japan (95) (96) (97), the Bahama Islands (98) and various islands of the Pacific, including Hawaii, led to the general conclusion that the rate of withdrawal from ground water storage in coastal areas should not exceed the rate of ground water recharge from rainfall.

The soundness of the foregoing conclusion has been amply demonstrated in the United States. Bacon and Parker (99) described salt water penetration a distance of almost two miles inland as a result of lowering the water table by a drainage ditch in southern Florida. Turner and Foster (100) reported sea water intrusion at depths below 1000 feet for distances up to 20 miles inland from Galveston. In 1940, Barksdale (101) found that salt water had encroached into a pressure aquifer in New Jersey a distance of two miles at a rate of one mile per six years. Some five years later considerable alarm began to be expressed in the literature in California. Simpson (102) noted in 1945 that 6000 acres in the Salinas Basin had been contaminated by sea water extending 1-3/4 miles inland at a rate of some 600 feet per year.

Remedial measures for southern California were suggested by Poland (103). Among those considered were balancing long-term basin-wide draft and replenishment; deviating through wells immediately inland from the saline front; and constructing impervious subsurface dykes.

Summaries of California conditions were presented by Banks and others (104) (105) in 1950 and 1951. At that time the most spectacular example of sea water intrusion was in the Manhattan Beach area of the West Coastal Basin where a saline front had advanced inland a distance of more that two miles under a landward gradient imposed by ground water levels 5 to 15 feet below sea level. The reports recommended experimental studies concerned with control of sea water by intrusion mounds of injected fresh or reclaimed water, and by impervious membranes. In 1952 a field scale experiment in control of sea water intrusion was begun at Manhattan Beach by the Los Angeles County Flood Control District, based on theoretical considerations and model tests reported by Baumann (106) in 1951. Model studies were begun at the same time by the University of California at Berkeley on the behavior of fresh water mounds and on the use of impermeable cut-off walls. As previously noted, all of these studies were made under the sponsorship of the California State Water Resources Board.

From the model studies with recharge wells a number of pertinent conclusions were reached.

Among other things it was found that, a) (as predicted by the Ghyben-Hertzberg principle) in order to prevent sea water from entering an aquifer which has direct access to the sea, the fresh water piezometric surface must be held above sea level a distance equal to at least (S-1)* times the distance from sea level to the lowest pumping zone to be protected, b) the maintaining of a fresh water surface above sea level by the above amount will result in a seward leakage of fresh water in the upper part of the aquifer, and c) if fresh water can be injected into the aquifer at a sufficient rate, the piezometric surface can be maintained at the required height above sea level in a region along the coast, but unless the inland demand for fresh water is reduced, the injection rate must equal not only the leakage rate but also the entire overdraft rate which originally caused the intrusion.

From this latter finding it is evident that ground water recharge would be more economical if some device other than an artificial pressure mound were used to control sea water intrusion and the waste water injected at some point further inland. Two possibilities were tried in the experiments: The creation of a pumping trough, and the use of cut-off walls.

A pumping trough, created by pumping line of wells along the seacoast at such a rate as to intercept sea water before it reaches the low pressure region on the landward side, shows promise as a device for preventing sea water intrusion. In model tests it was observed that 12 percent of the water pumped represented fresh water when the landward wedge of sea water was held stationary. This loss of fresh water did not exceed the flow of fresh water to the sea under natural or induced fresh water pressures necessary to hold stationary and intruding wedge of sea water.

Experiments with bentonite clay alone and in conjunction with various admixtures were run in an attempt to develop a relatively impermeable cut-off wall to reduce sea water intrusion. The chief value of such a cut-off wall would be that underground fresh water storage could be developed below sea level. This would create a greater capacity for salvage of fresh water which might otherwise escape to the ocean during wet years. The idea of such a sea water barrier evolved naturally from such experience as the successful use of puddle cores in earth dams, while the successful use of bentonite in well drilling muds and of various bituminous and cement mixtures in soil stabilization made such materials worthy of consideration for the construction of impermeable membranes underground. Some reports of placing cut-off walls in trenches appear in the literature. The construction of more than six miles of sub-levee cut-off trenches ranging in depth to 60 feet along the Columbia River is reported (107). Another (108) report describes the placing of a puddled clay cut-off wall around an oil field near Long Beach, California. In this case a ladder type trenching machine followed by continuous backfill was used, and although the cut was but 45 feet deep it is believed that much deeper cuts would be economically feasible.

The results of experiments indicate that it should be possible to construct cut-off walls of low permeability, although the least permeable mixtures pose difficult placement problems.

Direct Reuse of Waste Water

Approximately one half of the 224 municipalities, sanitary districts, and public and private institutions reported (19) (12) to be disposing of waste waters by methods associated with reclamation were in 1954 using sewage plant effluents to irrigate grass, orchards, and crops. This was reported to represent the sewage from an urban population of approximately 250,000, or some 25,000 acre feet of water per year, and to equal some 16 percent of the total urban sewage effluent in California going into watercourses, onto the land, or into recharge ponds. In contrast some 700,000 acre feet per year were wasted into saline waters of the state. Of this total an appreciable amount could presumably be utilized directly as irrigation water or reused by industry.

An intensive study (86) of utilization of waste waters by cities, industries, and individuals in California and in the southwest is being conducted by the University of Southern California under the sponsorship of the California State Water Pollution Control Board. This study is expected to yield important information on the extent, feasibility, and economy of re-use of domestic and industrial waste waters, and on its significance in terms of the total water economy of the state. Through cooperative work with cities and industry it is further intended that the study shall serve to help point the way to engineered reuse of waste waters which might better be used above the ground than recharged into the ground water. Both economic and water quality considerations are involved.

New or improved methods of waste water treatment hold promise of producing water of sufficiently high quality for direct reuse above ground, and of reclaiming water from organic industrial wastes presently extremely difficult of disposal. The effectiveness of customary treatment methods is constantly being increased. One

---

*S = specific gravity of the sea water.

of the most hopeful new methods seems to be the treatment of raw sewage, secondary sewage, or a variety of organic wastes in algal ponds. Experimental studies (109) (110) which have been in progress at the University of California at Berkeley since 1950, under a grant-in-aid from the National Institutes of Health, have demonstrated that an algal-bacterial symbiosis can be used to convert waste organic matter into high protein algal cells suitable for animal feed supplement. Research is continuing to determine the most economical method for harvesting the algae produced. The quality of the remaining liquid varies with the method of separation used but there is every indication that practical methods will produce an effluent of such quality that its reuse above ground by agriculture or industry will be economical.

The method is an outgrowth of the use of lagoons or oxidation ponds for the secondary treatment of sewage in many places in the southwest. Oxidation ponds themselves produce an effluent which in many cases can be used above ground more economically than by recharge into the ground water. They depend upon detention of the waste water in a pond long enough to allow sufficient oxygen for the stabilization of organic matter to diffuse downward from the atmosphere. Although algae appear in oxidation ponds their role in the production of oxygen for the stabilization process is a minor one. In the algal method, however, certain green algae are grown in large numbers simultaneously with bacteria in fresh organic wastes or sewage. When such growth is taking place biological oxidation by bacteria and photosynthetic reduction by algae proceed rapidly, each process aiding the other.

In the vicinity of metropolitan areas land suitable for sewage reclamation by algal culture may impose economical limits on the process. Where the process can be used, however, there is a good prospect for its being utilized to produce an effluent suitable for direct reuse, or in any event for ground water recharge, at a cost considerably below that of more conventional methods of sewage treatment.

Sea Water Conversion

Wherever water shortages have existed in coastal areas laymen as well as engineers and chemists have dreamed of reclaiming water from the ocean. Early experience in such reclamation was largely confined to distillation and the conclusion was soon reached that to obtain large amounts of water from the sea was economically infeasible. Nevertheless, the prospect of fresh water from the sea has never ceased to capture the imagination, and with the advent of the atomic age the citizen is convinced anew that one day the dream will become reality. In the meantime a vast amount of research has gone into various aspects of desalting sea water and into the exploration of methods which might prove effective. W. F. Langelier (111) has reported on fundamental studies of the control of scale in the distillation of sea water. As a result of some five years of study at the University of California under the sponsorship of the Corps of Engineers the need for mechanical descaling has been eliminated and methods substituted which offer several possibilities of effecting economics in distillation.

In 1951 Howe (112) (113) began a sea water conversion research program under a special appropriation by the California State Legislature. His work was later continued under the sponsorship of the U. S. Department of the Interior. The purpose of the original studies was to determine whether or not any of the methods of refining sea water could be used to supplement the water supplies of cities along the California coast. The objective of the program was the selection and development of procedures for demineralizing water, preferably at costs not to exceed $40 per acre-foot for irrigation waters and $125 per acre-foot for domestic supplies. Methods investigated included solar distillation, low temperature difference method of utilizing waste heat from steam plants, skimming, high pressures in combination with permeable membranes, and others. While none of these processes met the cost requirements of even domestic supplies their eventual use to supplement water supplies can not be dismissed.

As pointed out by Langelier (114) chemists have been somewhat more optimistic than engineers concerning the eventual large-scale recovery of fresh water from the sea. One of the most encouraging procedures is the application of permselective membranes to the electrochemical desalting of brines or sea water. Credit for pioneering in the application of this principle belongs to Ionics Inc., of Cambridge, Mass. (115). The process (116) utilizes the semipermeable properties of certain types of plastic membranes which allow only anions to pass in an imposed electrical field, in parallel with other such membranes which pass on cations. Early estimates of the cost of desalting sea water by the process now seem optimistic and it is doubtful that there is any immediate prospect of producing drinking water from the ocean by it at costs such as $125 per acre-foot. Nevertheless, the method had prospects for use on brackish waters, and eventually perhaps for use on more saline waters.

It is always possible that atomic power may become the answer to the problem of energy to reclaim sea water economically. In the meantime the oceans remain an obvious source of unlimited water and as such will continue to challenge the ingenuity of engineers and scientists. Present indications are that the reclamation of sewage plant effluents, which in California alone represents some one million acre-feet of water per year, will precede any reclamation of large amounts of water from the sea for the simple reason that it is easier to remove two tons of suspended and dissolved matter from a million gallons of water than it is to remove 125 tons of highly soluble matter from the same quantity.

SUMMARY

California's rapidly growing population with its accompanying expansion of industry and agriculture leads to an ever increasing demand for water. Intensive use of surface supplies and over-pumpage of ground waters, mostly since 1940, has led to declining water tables and, in many coastal areas, to a loss of producing aquifers to intruding sea water. Inevitably the state's search for water must lead to the reclamation of waters generally considered as municipal and industrial wastes, and perhaps even to the sea itself. Mindful of this situation, various public agencies including the University of California have sponsored research on various aspects of the problem. This report is intended to bring together and to evaluate the pertinent results of these studies, principally those in which the Sanitary Engineering Research Laboratory of the University played a part.

Domestic sewage represents one of the most important sources of reclaimable wastes, amounting in California to some one million acre feet annually, or about one-half of the present overdraft on ground water basins. Industrial waste waters, especially those from food processing and such others as can be kept separate from economically unreclaimable liquid wastes, are of increasing importance. Flood waters and surface drainage constitute another major source of reclaimable water, subject to their own peculiar problems and to seasonal occurrence. Then, too, there is the ocean, the very vastness of which challenges the imagination of man, often to the exclusion of less spectacular sources of reclaimable water.

Largely through a change in concept of water use, sewage treatment, plus discharge to a watercourse, is becoming recognized as a reclamation procedure. Newer methods currently attracting attention include ground water recharge through surface spreading, over-irrigation, or direct injection of waste or excess water into underground water-bearing formations. The advantages and shortcomings of these proposals determined as a result of experimental studies are outlined in the report, along with some of the problems of fresh water recovery from the ocean.

The fact that ground waters exist and are replenished by rainfall demonstrates that ground water recharge is possible. Engineered recharge, however, requires vastly increased recharge rates over relatively small areas, plus the introduction of waters of a quality loss suited to entering the ground. Thus technical problems are involved. Accompanying such problems are legal questions of profound consequence. For the purpose of the report, however, it is assumed that legal questions are not insurmountable if water reclamation is technically feasible.

Recharge by Spreading

In 1953 some 219 recharge undertakings were reported to be in operation in 32 states, about one half of these being in California. Among the best known are the vast fresh water spreading operations of Los Angeles County Flood Control District, and the direct recharge of well waters on Long Island. Many of the others are empirical attempts to dispose of waste waters by surface ponding. In 1930 is was shown in Los Angeles that a highly treated sewage plant effluent could be safely returned to the ground water. Further tests at Whittier and Azusa in 1949 showed that much rougher sewage plant effluents could be recharged into the ground water. Spreading studies with surface waters were begun at Bakersfield in 1936, and for the past ten years have been continued by the Soil Conservation Service. From these studies have come some of the most significant contributions to our knowledge of the phenomena of infiltration and percolation. Studies with sewage plant effluents have been conducted at Lodi, California and at Richmond, California by the University of California, under its own and other public sponsorship. In all of these studies various operational procedures and soil treatments have been investigated with the general conclusion that water or sewage plant effluent can be returned to the ground water without danger to the public health through pollution travel, and at rates of from 0.5 to 1.0 acre feet per day per acre of surface spread. The known principles of infiltration and percolation are discussed in the report, and data presented to show the limited nature of bacterial movement in soils. Experiments are also reported which show the feasibility of predicting the field performance of soils on the basis of relatively simple lysimeter studies.

Recharge by Injection

For more than 25 years the direct recharge of underground water-bearing formations has been seriously considered. For a number of reasons the method might be preferable to surface spreading. The possibility of creating a hazard to the public health as a result of bacterial or chemical pollutants moving with the ground water has, however, been a deterring factor.

Another drawback has been the known ability of suspended solids in a water to clog the pores of an aquifer, thus making continuous recharge impossible. In combination, these two factors have made the direct recharge of sewage plant effluent seem both hazardous and difficult in the extreme unless expensive works were constructed to upgrade the quality of the waste water, in which case it might better be utilized directly. Nevertheless, treated sewage continues to represent such an impressive volume of water that its reclamation by ground water recharge continues to hold economic possibilities in water-short areas, provided public health considerations and technical problems are not insurmountable.

Reported experience in ground water recharge is quite limited, the most extensive being in oil fields where injection of brines into deep strata of low permeability has been accomplished at rates of from 0.15 to 1.0 gallons per minute per foot of aquifer. Successful ground water recharge with fresh water at Long Island, however, has been accomplished at rates up to some 8.5 gal/min/ft of aquifer thickness. These experiences, contributed little if anything to a knowledge of operational and pollution travel problems associated with the injection of waste waters, such as sewage, containing suspended and dissolved organic matter. Accordingly, the California State Water Pollution Control Board sponsored a 44-month field study of direct recharge into underground formations. The work was carried out by the University of California at its Engineering Field Station in Richmond, California. A summary of this investigation is presented in this report along with data on some other pertinent studies.

In the Richmond studies fresh water was recharged into a pressure aquifer having a permeability of about 1900 gal/sq ft/day at a rate of 8.4 gal/min/foot of aquifer (about one-half the safe yield of the well under pumping) for long periods without difficulty. The addition of sewage plant effluents at the same rate, however, caused clogging of the well at a rate proportional to the amount of solids injected. Under permissible well head pressure buildup, a sewage equivalent to the final effluent from secondary sewage treatment could be injected for about 9 or 8 days. At that time redevelopment was necessary. Chlorine injection followed by a half day of contact and three or four hours pumping at a rate equal to twice the injection rate completely re-established the ability of the aquifer to receive injected water. The discharged water amounted to some four percent of that recharged and was easily separated from its suspended solids for reinjection underground if desired. Experience with recharge well operation demonstrated the necessity for gravel packing of the recharge well.

Public Health Aspects

The downward movement of bacteria with percolating water is shown to be of little concern, both by previously reported experience and by experiments under field and pilot plant conditions. In fine soil at Lodi, California, a bacterially acceptable water by USPHS Standards was obtained by percolation through four feet of soil. Observations with coarser soils showed a greater depth of penetration but no situation developed which would be of serious public health significance in a practical spreading operation, although it must be presumed that some organisms will reach the ground water under certain conditions discussed in the report. The nature of bacterial removal by soils is presented in some detail.

The travel of bacteria with moving ground water was observed in detail in the Richmond experiments. Sewage effluents containing coliform concentrations as great as 4.7×10^6 organisms per 100 ml were injected at various rates. In no case did observed travel exceed 100 feet in the direction of ground water flow, or 63 feet in other directions. Concentrations of organisms at these distances were 23 or less per 100 ml. The removal of bacteria by an aquifer is shown to be a function of distance and aquifer filterability rather than of rate of recharge. The conclusion is reached that the reclamation of waste water by direct recharge into sand aquifers is not limited by public health considerations. It is recommended, however, that provision for monitoring the ground water bacterially and chemically be a part of any practical recharge project.

Travel of chemical pollutants with ground water is not limited in the manner observed for bacteria except in the case of biochemically unstable dissolved matter. Consequently it may be presumed that industrial wastes carrying toxic or noxious chemicals must generally be excluded from waste waters to be injected underground.

Engineering and Economic Aspects

Results of studies discussed in the report show that no special treatment is necessary to prepare a final sewage plant effluent for ground water recharge by spreading or injection. Suitable operational procedures are discussed and involve no unresolved engineering problems with either waste or flood waters. Over-irrigation, however, is shown to be a generally impractical method of ground water recharge because of geological limitations on its applicability and difficult legal considerations. Normal irrigation, however, may be an economical method of utilizing certain waste waters directly.

From an economic standpoint the cost of installing and operating recharge wells is governed by the cost of making usual geological investigations, constructing wells of a normal type, and installing and operating ordinary water handling equipment. Therefore, water reclamation by ground water recharge is subject to a straightforward engineering analysis. Reclamation of sea water, brackish waters, and other presently unused waters is under intense investigation but methods are not yet sufficiently economical for widespread production of public and agricultural water supplies.

REFERENCES

1. Ground Water Conditions in Mendota-Huron Area, Fresno and Kings County, California, Report U. S. Geological Survey, Ground Water Branch, June 1954.

2. Banks, H.O., Richter, R.C., Sea-Water Intrusion Into Ground-Water Basins Bordering the California Coast and Inland Bays, Transactions, American Geophysical Union, Vol. 34, No. 4, August 1953.

3. Krone, R.B., McGauhey, P.H., Gotaas, H.B., Annual Report of Investigation of Travel of Pollution (unpublished report to Calif. State Water Pol. Control Board) July 1953.

4. Final Report on Investigation of Travel of Pollution (report to Calif. State Water Pollution Control Board by Sanitary Engineering Research Laboratory, University of California, Dec. 1954) Calif. State Water Pollution Control Board, Publication No. 11, 1954.

5. Report on Laboratory and Model Studies of Sea Water Intrusion (report to Calif. State Water Resources Board, Sept. 1953) Technical Bulletin No. 11, I.E.R. Series 37, Sanitary Engineering Research Laboratory, University of California, March 1955.

6. An Investigation of Sewage Spreading of Five California Soils, Technical Bulletin No. 12, I.E.R. Series 37, Sanitary Engineering Research Laboratory, University of California, April 1955.

7. Kaufman, W.J., Klein, G., Removal of Radioisotopes by Sewage Treatment Processes, (report to Atomic Energy Commission) March 1952.

8. Kaufman, W.J., Klein, G., Concentration of Radioisotopes by Activated Sludge, (report to Atomic Energy Commission) June 1954.

9. Kaufman, W. J., Klein, G., Biological Treatment of Radioactive Wastes, (report to Atomic Energy Commission) June, 1954.

10. Field Investigation of Waste Water Reclamation in Relation to Ground Water Pollution. (Report to Calif. State Water Pollution Control Board by Sanitary Engineering Research Laboratory, University of California, June 1952) State Water Pollution Control Board Publication No. 6, 1953.

11. An Abstract of Literature Pertaining to Sea Water Intrusion and Its Control. (Report to Calif. State Water Resources Board, July 1952) Technical Bulletin No. 10, I.E.R. Series 37, Sanitary Engineering Research Laboratory, University of California, March 1951.

12. Present Economic And Technical Status of Water Reclamation from Sewage and Industrial Wastes. Technical Bulletin No. 4, I.E.R. Series 37, Sanitary Engineering Research Laboratory, University of California, March 1951.

13. Lane, D.A., Increasing Storage by Water Spreading, Jour. Am. Water Works Assn., 26, 4, 421-9, April, 1934.

14. Harrell, Marshall A., Artificial Ground Water Recharge - A review of investigations and experience, USGS unpublished paper, 1935.

15. Laverty, F.B., Water Spreading Operations in the San Gabriel Valley, Jour. A.W.W.A., 46, 2, 112-122, February, 1954.

16. Goudey, R.F., Sewage Reclamation Plant for Los Angeles, Western Construction News, 5, 20, 519-25, October, 1930.

17. Arnold, C.E., Hedger, H.E., Rawn, A M, Report Upon Reclamation of Water from Sewage and Ind. Wastes in L.A. County, Calif., Planograph, April 1949. (Abstracted in Pub. Health Engr. Abs. xxx:5:23 (1950))

18. Freeman, V.M., Preliminary Report on Cost of Reclaiming Water From the Oxnard Sewer Systems, September, 1949.

19. Studies of Waste Water Reclamation and Utilization. (Report to Calif. State Water Pol. Control Board by University of California, Los Angeles, January 1954). State Water Pol. Control Board Publication No. 9, 1954.

20. Anon., Committee on Artificial Ground Water Recharge, Am. W. W. Assn., Artificial Ground Water Recharge, Progress Report, Jour. Am. Water Work Assn. 44, 8, 682-4, August, 1952.

21. Muckel, D.C., Research in Recharging Ground Water Supplies by Spreading, paper prepared for the U.S. Dept. of Agriculture, 11 pp, April, 1950.

22. Bliss, E.S., Johnson, C.E., Schiff, L., Report on Cooperative Water Spreading Study With Emphasis on Laboratory Phases. Provisional

Report, Soil Conservation Service, U. S. Dept. of Agriculture, December, 1950.

23. Schiff, L., An Exploratory Study of the Effect of Surface Head on Infiltration Rates Under Water Spreading Conditions, Provisional Report presented May 7, 1952, American Geophysical Union Meeting, Washington, D. C.

24. Schiff, Leonard, Some Developments in Water Spreading. Provisional Report, Soil Conservation Service, U. S. Dept. of Agriculture, September, 1952, Supplemented November, 1953.

25. Schiff, Leonard, Water Spreading for Storage Underground. Agricultural Engineering, 35, 11, 794-800, November, 1954.

26. Ferris, J.G., Water Spreading and Recharge Wells, Proc. Ind. Water Conservation Conference, 15 pages, January, 1951.

27. Tibbetts, F., Experience With Ground Water Replenishment in Santa Clara Valley, Jour. Am. Water Works Assn., 30, 2, 326, February, 1938.

28. Stone, R., Garber, W.F., Sewage Reclamation by Spreading Basin Infiltration, A.S.C.E., Proc. Separate No. 87, Vol. 77, September, 1951.

29. Christiansen, J.E., Magistad, O.C., Report for 1944, Laboratory Phase of Cooperative Water-Spreading Study. U. S. Regional Salinity Laboratory (unpublished).

30. Bodman, G.B., The Variability of Permeability Constant at low Hydraulic Gradients During Saturated Water Flow in Soils. Soil Science Society Proceedings, 45-53, 1937.

31. Allison, L.E., Effect of Micro-organisms on on Permeability of Soil Under Prolonged Submergence. Soil Science, 63, 6, 439-450, June, 1947.

32. Harrell, M.A., Artificial Ground Water Recharge - A review of investigations and experience U.S.G.S. unpublished paper, 1935.

33. Meinzer, O.E., General Principles of Artificial Ground Water Recharge. Econ. Geology, 41:191 (1946).

34. Laverty, F.B., Ground Water Recharge, Jour. Am.Water Works Assn., 8,667-81, August 1952.

35. Brashears, M.L., Recharging Ground Water Reservoirs With Wells and Basins, Mining Engineering Trans. 5, pp. 1029-32, October, 1953.

36. Lane, D.A., Artificial Storing of Ground Water by Spreading, Jour. Am. Water Wks. Assn. 28, No. 9, pp 1240-51, September 1936.

37. Holbrook, G.W., Young, W.H. Jr., Technology of Water Injection in the Aleghany Field, New York, A.P.I. Drilling and Prod. Pract. p. 65-76, 1945.

38. Heithecker, R.E., Some Methods of Separating Oil and Water in West Texas Fields, and Disposal of Oil Field Brines in the Hendricks Oil Field, Texas, U. S. Bureau of Mines, Report of Investigations, R. I. 3173, May 1932.

39. Hughes, R.V., Pfister, R.J., Advantages of Brines in Secondary Recovery, AIME Transactions-Petroleum Division, Vol. 170, 1947, pp 107, and discussion p. 199, references p. 198.

40. Alcorn, I.W., Salt Water Injection Systems, Oil Weekly, 110 (13) p. 20-24, 1943.

41. Schmidt, Ludwig, Divine, J.M., The Disposal of Oil Field Brines, U.S.B. Mines Report of Investigations, R. I. 2945, June 1929.

42. Rhea, A.S., Miller, E.B. Jr., Disposal of Salt Water in the East Texas Field, AIME, Pet. Tech., TP 1678, January 1944.

43. Plummer, F.B., Effect of Certain Microorganisms on the Injection of Water Into Sand, AIME, Pet. Tech., TP 1678, January 1944.

44. Riggs, C.H., Smith W.C., Water Flood Oil Recovery, Oil and Gas Jour. pp. 117, May 31, 1951.

45. Reed, P., Magnolia Water Project Represents Advance in Disposal Technique. The Oil and Gas Jour. p. 30, December 22, 1938.

46. Reed, P., Policies and Results of Water Flooding in Kansas. Oil and Gas Jour. p. 31, December 3, 1942.

47. Simons, H.F., Efficient Plant Used in Illinois for Salt-Water Disposal. Oil and Gas Jour., 39, 9, 32-33, January 2, 1941.

48. Dial, L.H., Disposal of Salt Water in the East Texas Field. The Petroleum Eng. p. 59, November, 1943.

49. Lyon, Richard B., Cashell, J., Water Injection in the Chatham Field, Medinia Co., Ohio. A.P.I A.P.I. Drill. and Prod. Prac., p. 84, 1945.

50. Terrill, C.F., Water Injection in the Cabin Creek Field West Virginia, A.P.I. Drill and Prod. Pract. p. 77-83, 1945.

51. Cecil, L., Underground Disposal of Process Waste Water. Industrial and Engineering Chemistry, 42, 594-99, April 1950.

52. Sundstrom, R.W., Hood, J.W., Results of Artificial Recharge of the Ground Water Reservoirs at El Paso Texas. Texas Board of Water Engrs. Bul. 5206, 19 pp. July 1952.

53. Johnson, A.H., Ground Water Recharge on Long Island. American Water Works Assn. Jour. 40, 11, 1159-66, November 1948.

54. Butler, R.G., Orlob, G.T., and McGauhey, P.H., Underground Movement of Bacterial and Chemical Pollutants. Jour. Am. Water Works Assn. 46, 2, pp. 97-111, February 1954.

55. Kligler, I.J., Investigation on Soil Pollution and Relation of Various Types of Privies to Spread of Intestinal Infections. Monograph 15. Rockefeller Inst. Medical Research, New York (Oct. 10, 1921).

56. Caldwell, E.L., Studies of Subsoil Pollution in Relation to Possible Contamination of Ground Water From Human Excreta Deposited in Experimental Latrines. J. Infectious Diseases, 62, 273 (1938).

57. Mom, C.P., and Schaafsma, N.D., Disposal of Fecal Matter and Pollution of Soil in the Tropics. Mededeel. Dienst Volksgezondheid Nederland. Indie, 22:161, (1933); abstracted, Pub. Health Eng. Abstracts, 15, 5, 48 (Aug. 3, 1935).

58. Stiles, C.W. and Crohurst, H.R., The Principles Underlying the Movement of B. coli in Ground Water with the Resultant Pollution of Wells. Pub. Health Reports, 38, 1350, June 1953.

59. Stiles, C.W., Crohurst, H.R. and Thomas, G.E., Experimental Bacteria and Chemical Pollution of Wells via Ground Water, and the Factors Involved. Hyg. Lab. Bul., No. 147, June 1927.

60. Hofman, E.F., The Protection Against Pollution of Water Supplies Drawn From Ground Water and Spring Water, Gas. u. Wasser (Germ.) 84, p. 709 ('41) Abstracted in JAWWA 38:438.

61. Dyer, B.R., Bhaskaran, T.R., The Present State of Our Knowledge of Soil and Ground Water Pollution. Indian Medical Jour. LXXVIII, 11, 561-63, 1943.

62. Ditthorn, F., Lauerssen, A., Experiments on the Passage of Bacteria Through Soil, Eng. Record, 60, 642, December 1909.

63. Caldwell, Pollution Flow From a Pit Latrine When Permeable Soils of Considerable Depth Exist Below the Pit. J. Infectious Disease, 62:125, 1938.

64. Caldwell, E.L., Study of an Envelope Pit Privy. J. Infectious Diseases, 61:264, 1937.

65. Caldwell, E.L., Pollution Flow From Pit Latrines When an Impervious Stratum Closely Underlies the Flow. J. Infectious Diseases, 61, 270, 1937.

66. Caldwell, E.L. and Parr, L.W., Ground Water Pollution and the Bored-Hole Latrine. J. Infectious Diseases, 61, 148, 1937.

67. Warrick, L.F. and Tully, E.J., Pollution of Abandoned Well Causes Fond DuLac Typhoid Epidemic, Eng. N-R 104-410-1. March 6, 1930. (Abst. JAWWA 23:298, 1931).

68. Dappert, A.F., Tracing Travel and Changes in Composition of Underground Pollution, Water Works and Sewage, V 79, 8, August 1932, pp. 265-9.

69. Meinzer, O.E., General Principles of Artificial Ground Water Recharge. Econ. Geology, 41, 191 (1946).

70. Sampson, G.A., Engineering Problems Connected with Recent Improvements to Newton, Mass., Water Supplying Works, J. NEWWA, 48, 88, 1934.

71. Austen, W., Supplementing Ground Water — Physical and Chemical Observations, Gas-u. Wasserfach (Ger.), 82:606 (1939); abst. JAWWA 38, 439, March, 1946.

72. Holthusen, W., Ground Water Replenishment, Zietchfift, Cl. Vero Deutsh Ingenieure, 77, 37, 1013, Sept. 1933 (Abst. JAWWA 27, 130 and 27, 538.)

73. Lang, A., Pollution of Water Supplies, Especially of Underground Streams, by Chemical Wastes and by Garbage. Z.Gesundheitstech. u. Stadtehyg. (ger.) 24, 5, 174 (May 1932); abst. JAWWA, 25, 1181, August 1933.

74. Lang, A., Gruns, H., On Pollution of Ground Water by Chemicals, Gas u. Wasser 83, 6, (Jan. 6, 1940) Abst. JAWWA 33:2075.

75. Rossler, B., The Influencing of Ground Water by Garbage and Refuse Dumps, Vom Wasser (Ger.), 18, 43, 1950-51.

76. Austen, W., Physical, Chemical, and Bacteriological Changes in Ground Water Due to Unfiltered Surface Water. Vom Wasser (Ger.), 15, 1941-42. Abst. JAWWA, 38, 438, March 1946.

77. Blakely, L.E., The Rehabilitation, Cleaning, and Sterilization of Water Wells. Jour. Am. Water Works Assn. 37, 1, 101, January 1945.

78. Well Pollution by Chromates in Douglas, Mich. Mich. Wtr. Wks. News, 7, 3, 16, July 1947.

79. Davids, Herbert W. and Leiber, Maxim, Underground Water Contamination by Chromium Wastes, Water and Sewage Works 98, 528-34, 1951.

80. Calvert, C., Contamination of Ground Water by Impounded Garbage Wastes. Jour. Am. Water Works Assn. 24, 266, February 1932.

81. Sayre, A.N. and Stringfield, V.T., Artificial Recharge of Ground Water Reservoirs, Jour. Am. Water Works Assn. 40, 11, 1153, November 1948.

82. Muller, Josef, Contamination of Ground Water Supplies by Gasoline, Gas-u. Wasser. 93, 205-9, 1952.

83. Fox, C.S., Radioactive Isotopes Tracer Underground Water, Pub. Works, 83, pp 57-8, January 1952.

84. Harmon, B., Contamination of Ground Water Resources. Civ. Eng. 11, 343, 1941.

85. Cobleigh, W.M., Special Applications of Chemical Data to Water Supply Investigations, Abst. Bact., 5:26, 1921, abst. JAWWA, 13:259, February 1925.

86. Waste Water Reclamation and Utilization. Study Conducted by University of Southern California for California State Water Pollution Control Board. (in progress)

87. Los Angeles County Flood Control District. Report to the California State Water Resources Board on Investigational Work for Prevention and Control of Sea Water Intrusion. Jan. 22, 1955.

88. Badon Ghyben, W., Nota in verband met de voorgenomen put boring nabij Amsterdam: K. Inst. Ing. Tijdschr., 1888-89, p.21, The Hague, 1889.

89. Braithwaite, F., On the Infiltration of Salt Water Into the Springs of Wells Under London and Liverpool, Proceedings Inst. of Civil Engineers, London, vol. 14, pp. 507-523, 1855.

90. Herzberg, Bairat, Die Wasserversonrgung einiger Nordseebader: Jour. Gasbeleuchtung und Wasserversorgung, Jahrg. 44, Munich, 1901.

91. d'Andrimont, R., Notes sur l'hydrologie du littoral belge (Notes on the hydrology of the Belgium coast), Soc. Geol. Belgique Annales, vol. 29, pp. M129-M144, Liege, 1902.

92. Van Ertborn, O., Quelques mots as sujet de l'hydrologie de la cote belge (A few words on the subject of the hydrology of the Belgium coast), Bulletin de la Societe Belge de Geologie de Paleontologie et d'Hydrologie, vol. 16, pp. 517-521, 1902.

93. Pennink, J.M.K., Investigations for Ground-Water Supplies. Trans. Amer. Soc. of Civil Engineers, Vol. 54-D, pp 169-181, 1905.

94. Dubois, E., Etudes sur les eaux souterraines des Pays-Bas (Studies of the Ground Water of the Netherlands). Musee Teyler Archives, 2nd. ser., vol. 9, pp. 1-96, Haarlem, 1905.

95. Hayami, S., On the saline disaster and variation of coastal underground water by land subsidence accompanying the great earthquake of December 21, 1947, Commission des Eaux Souterraines, International Union of Geodesy and Geophysics, Ninth General Assembly, Brussels, 1951. (unpublished)

96. Kitagawa, K., Un Aspect du development des etudes des eaux souterraines au Japan (An aspect of the development of ground water studies in Japan), Japanese Journal of Astronomy and Geophysics, vol. 17, no. 1, pp. 141-155, 1939.

97. Toyohara, Y., A study on the Coastal ground water at Yumigahama, Tottori, Memoirs of the College of Science, Kyoto Imperial University, Series A, 18, 5, 295-309, 1935.

98. Riddel, J.O., Excluding Salt Water From Island Wells - A Theory of the Occurrence of Ground Water based on Experience at Nassar, Bahama Islands, Civil Engineering, 3, 7, 383-385, 1933.

99. Brown, R.H. and Parker, G.G., Salt Water Encroachment in Limestone at Silver Bluff, Miami, Florida. Economic Geology, 40, 4, 235-262, 1945.

100. Turner, S.F. and Foster, M.D., *A Study of Salt-Water Encroachment In the Galveston Area.* Trans. Amer. Geophys. Union, pp. 432-435, 1934.

101. Barksdale, H.C., *The Contamination of Ground-Water by Salt Water Near Parlin, New Jersey.* Trans. Amer. Geophys. Union, pp. 471-474, 1940.

102. Simpson, T.R., *Salinas Basin Investigation.* Calif. Div. of Water Resources, Bulletin 52, Sacramento, Calif., pp. 138-139, 1946.

103. Poland, J.R., *Summary Statement of Ground-Water Conditions Along the Coast of Orange County, California.* Directors of Orange County Water District, 20 pp. plus 11 pl., 1947.

104. Banks, H.O., Gleason, G.B. and Richter, R.C., *Sea-Water Intrusion Into Ground Water Basins Bordering the California Coast and Inland Bays,* Report No. 1, Water Pollution Investigations, Div. of Water Resources, State of California, 23 pp., Sacramento, 1950.

105. Banks, H.O. and Bookman, M., *Proposed Investigational Work for Control and Prevention of Sea-Water Intrusion Into Ground Water Basins,* Report to State Water Resources Board, Div. of Water Resources, State of Calif., 33 pp., Sacramento, 1951.

106. Baumann, Paul M., *Ground Water Movement Controlled Through Spreading.* Proc. Separate No. 86, Vol. 77, 38 pp., August 1951.

107. Anonymous, *Digging A Trench To Keep Water Out Under Columbia River Levees.* Western Construction, 27, 6, 107-108, June, 1952.

108. Rhodes, A.D., *Puddled-Clay Cutoff Walls Stop Sea-Water Intrusion.* Civil Engineering, 21, 2, 21-23, 1951.

109. Oswald, William J., and Gotaas, Harold B., *Photosynthesis in Sewage Treatment.* Presented before A.S.C.E., New York, N. Y., (Oct. 1954).

110. Gotaas, H.B., Oswald, W.J. and Ludwig, H.F., *Photosynthetic Reclamation of Organic Wastes.* Scientific Monthly 79,6. (Dec. 1954.)

111. Langelier, Wilfred F., *Discussion, Sea Water as a Source of Fresh Water,* Jour. Am. Water Works Assn., 44, 8, 697-700, August 1952.

112. Howe, Everett D., *Sea Water As a Source of Fresh Water.* Jour. Am. Water Works Assn., 44, 8, 690-697 August 1952.

113. Howe Final Report.

114. Langelier, Wilfred F., *Mechanism and and Control of Scale Formation in Sea Water Distillation.* Jour. Am. Water Works Assn., 46, 5, 461-469, May 1954.

115. *Permionic Membrane Demineralization.* Ionics, Inc., Cambridge, Mass. Bulletin No. 2, 1952.

116. Eliasson, Rolf, *Reclamation of Saline Waters by Electrodialysis shows Promise.* Civil Engineering, 34, 6, 44-47, June 1954.

TECHNICAL BULLETINS

SANITARY ENGINEERING RESEARCH LABORATORY
University of California
1301 S. 46th Street
Richmond 4, California

Number	Title	Price
1	Composting for Disposal of Organic Refuse	Not Available
2	Bibliography On Disposal of Organic Refuse By Composting	No Charge
3	Bibliography On Incineration Of Refuse	No Charge
4	Present Economic and Technical Status of Water Reclamation From Sewage and Industrial Wastes	No Charge
5	Municipal Incineration: A Study of the Factors Involved In Municipal Refuse Disposal by Incineration	$1.00
6	Municipal Incineration: A Field Study of Performance of Three Municipal Incinerators	$1.00
7	Tests On Deodorizing Mufflers	Not Available
8	An Analysis of Refuse Collection and Sanitary Landfill Disposal	$1.50
9	Reclamation of Municipal Refuse by Composting	$1.00
10	An Abstract of Literature Pertaining to Sea Water Intrusion and Its Control	$1.00
11	Report On Laboratory and Model Studies of Sea Water Intrusion	$1.00
12	An Investigation of Sewage Spreading on Five California Soils	$1.00
13	Studies in Water Reclamation	$1.00