About The Authors

Michael D. Campbell, as Director of Research of the National Water Well Association's Research Facility, Columbus, Ohio, is involved in research in high priority areas of ground water exploration, development, conservation and pollution control. A graduate of the Ohio State University, he has lectured on exploration drilling and development in Australia and the United States and has produced numerous publications and reports on shallow drilling technology, mineral exploration, water well technology, and water systems development.

Jay H. Lehr is Executive Director of the National Water Well Association; Editor of *Ground Water;* and Publisher of the *Water Well Journal.* After graduating from Princeton University, he received the nation's first Ph.D. in Hydrology for his work on the hydrodynamics of ground water from the University of Arizona. As a professor of both the University of Arizona and The Ohio State University, Dr. Lehr conducted extensive research on ground water pollution and oil well brine disposal in Ohio. He has published widely on such topics as hydrodynamics of ground water, ground water development and pollution control.

McGraw-Hill
Book
Company

Serving the
Need for Knowledge
1221 Avenue of the Americas
New York, New York 10020

A Contribution of the Research Facility of the National Water Well Association

Campbell
Lehr

water well technology

water well technology

Michael D. Campbell
Jay H. Lehr

water well technology

Field Principles of Exploration Drilling and Development of Ground Water and Other Selected Minerals

Michael D. Campbell
Jay H. Lehr

Sponsored by the Offica of Water Resources Research, U. S. Depertment of Interior, Washington, D. C.

For professionals or students in all sectors of the ground water, petroleum, and mining industries — water and oil well contractors, equipment manufacturers, exploration companies, and state and federel geologists and engineers — there is simply no other book available on the economic development, conservation, and pollution control of one of tha world's most important naturel resources: ground water. Technologically sound, absolutely current, this is the first work to cover the entire spectrum of water well technology. Since national, even international, concern is currently focusing on the problem of the pollution of our naturel resources, this "state of the art" on water well construction technology is particularly timely. It reviews current well construction methods end techniques used in the petroleum, mining, end ground water industries and brings together in one source the widely scattered technical information on well technology. The treatment stresses the basic principles of shallow drilling and development of ground water as well as other economic minerals found in the same geologic environment as ground water. It succinctly surveys the complex processes involved in correcting such problems as inefficiencies in water supply production, water quality deterioration, and inequities in water system economics due to incrustation/corrosion of the well structure, etc. It also reviews in detail the present state of the art of the technology both in a practical field-oriented way as well as in a way that the research scientist will find appropriate for his investigative

(continued on the back flap)

(continued from the front flap)

purposes. For the petroleum production engineer using water flood techniques in working over old gas and oil fields to develop new fuel supplies to meet the approaching energy crisis, the authors provide the technical know-how necessary for effective water source development and provide a key to relevant literature on water well design, maintenance, end general technology.

Similarly, mining operators who develop ground water supplies for washing, cleaning, or partial benefication of ore products will find this a practical source of information for water supply development and maintenance technology. Specific topics covered include — ground water pollution; rock drillability; cable-tool, rotary, variations of common drilling systems; new and future drilling systems; formation identification and evaluation; and well hydraulics, design, construction, efficiency, maintenance and cost analysis. Special features include — an annotated bibliography of some 673 entries — a 455-entry glossary of petroleum, mining, end ground water terms — and a comprehensive subject index of approximately 1,550 entries.

Praise from prepublication reviewers . . .

"We compliment you on synthesizing the vast amount of data covering many disciplines and we look forward to publication of this text. It is timely and I am certain that it will be used extensively by all members of the profession."

R. K. Blankennagel, Research Hydrologist, U. S. Geological Survey, Water Resources Division, Denver.

"The water well and oil well construction industries should profit greatly from the information you have compiled. The work has long been needed in both fields and your treatment is sound, straight-forward end generally complete. You are to be complimented for a job well done."

W. H. Walker, Senior Hydrologist, Illinois State Water Survey, Urbana.

"You have done an excellent job on a monumental task."

T. P. Ahrens, Senior Research Geologist, U. S. Dept. of Interior, Bureau of Reclamation, Denver.

"I am confident that the ground water industry will find the text very helpful in the solution of vital problems."

James C. Warman, Director Water Resources Research Institute, Auburn University, Alabama.

(Jacket designed by **Shaylah Fletcher**)

water well technology

Field Principles of Exploration Drilling and Development of Ground Water and Other Selected Minerals

Michael D. Campbell
Jay H. Lehr

McGRAW-HILL BOOK COMPANY
New York St. Louis San Francisco Düsseldorf London
Johannesburg Kuala Lumpur Mexico Montreal New Delhi
Panama Rio de Janeiro Singapore Sydney Toronto

Contents

Foreword

"Water, water everywhere, nor any drop to drink" comes not only from the ancient mariner, but also from the contemporary one. For in looking down at the earth from the "bridge" of a spacecraft in orbit,one has the impression that nearly the whole globe is water — and definitely inaccessible! But there are, in reality, two vast oceans — the obvious universal ocean one can see draping the globe, and the unseen ground water resources filling the porous crust of mother earth. This bit of data is not new — but the academic nature of that knowledge has been transformed into a physical visceral reality for a few who have orbited the earth for days on end.

In a spacecraft circling the globe, when you're not busy with navigation, experiments, or housekeeping, it is great fun to drag out the map, set the orbit trace through your present position, and look ahead to see what is coming up. "Hey, we'll be going right over Cairo, troops," or "Acapulco coming up just south of track in 10 minutes." And then into the night, the earth's shadow, the lightning flashes of thunderstorms over equatorial Africa, the faint airglow in its nocturnal evolution defining the night horizon, and dawn! Rapid, majestic dawn; and below, almost invariably the western Pacific. The Pacific and the long wait. For even at 17,000 mph, it seems forever before that vast blue expanse of water surrenders to the West Coast of North America. The human eye can see the rivers of the continents pour back into the ocean from where they came. The space ship's infrared eyes can likewise photograph the flow of cool underground waters from their coastal aquifers welling up beneath the ocean depth.

Then the fun of skipping across the states. City to city, following the interstate highways, marveling at the white rockies disappearing into the northern horizon. All these different cloud patterns over the ocean — all apparently independent , sometimes arranged in groups of honeycomb cells with lines of ocean between them, like an onion skin through a microscope. And sometimes long parallel lines of clouds, streaking along wind lines from nowhere to nowhere. Why? All that sunlight falling on the scene, heating things at different rates. We know there are tremendous exchanges of energy going on down there — between the ocean and the air and, in turn, between the air and the land. But what specific processes are involved and what factors control the energy flow across the boundaries? Can we predict what sea state will result in four or five days as a result of our observations today? Can we measure the depth and thickness of our underground reservoirs destined to provide the earth's water supplies for centuries to come? Not yet! But with finer measurements, better "eyes," infrared sensitive ones, microwave sensitive ones — maybe.

And what about the land? If the ocean in its dance with the atmosphere is quietly mysterious about this relationship, the land puts out a veritable cacophony of intermingled data. The checkerboard of field and meadow, brown and green to the eye, releases a wealth of information to the trained camera or infrared detector: the presence of significant shallow ground water supplies made evident by patches of lush vegetation amidst only mediocre crop land; the stress of wheat with too little water, or a pine forest infested by bark beetles or citrus trees under attack by Brown Soft Scale — all broadcast observable symptoms. These are the eyes we need for diagnosis.

And water too — how much snow is trapped up there in those mountains? How deep is it, and what is its density? How fast is it melting? What significance does it have to us? Inaccessible by foot and shrouded by clouds, the secret is well protected; except that microwave radiation doesn't honor the overcast. It passes through, oblivious to the cloud's existence and bounces off the snow, coded now with valuable data. But we don't yet know how to fully interpret the data from this probe. One day we may, and combined with soil moisture information and meteorological data, we may be able to deduce the total input of water a mile or more into the earth where the availability of ground water is limited by the denseness of the earth. This same ground water may be drilled by either a rock bit or perhaps one day soon, by laser. And if we're smart enough to do that, we should be able to construct a model which would then allow us to follow that water through its cycle back to the ocean and atmosphere. But what a lot of work ahead! New eyes to see and larger and more flexible brains (computers) may yet let us better manage and control our actions to harmonize with the environment on which we depend.

Interdependence — a key word. As soon as one grapples with problems on a global scale (whether hydrology, agriculture, oceanography, demography, meteorology, etc.), one is struck by the interdependence of these disciplines. If the boundaries are narrow enough, one can isolate the subject of interest and approach a single academic, pure, variable problem. But we now circle the globe in ninety minutes, and we cross all boundaries, real and man-made. And as this descriptive fact becomes a repetitious experience, the old human tendencies toward isolation and separation become inadequate for the situation. This is true both technically and humanistically.

Not that specialization is outdated. Far from it. But specialization in isolation is. What the oceanographer is discovering on his frontier is of interest to the geologist. And the ground water geologist is finding that the precious resource he deals with can be better managed if he takes advantage of the capabilities of the latest drilling and development technology, techniques and knowledge being born the world over in related disciplines such as gas and oil development, mineral exploration, and mining engineering. Interestingly enough, these interdependencies have always existed; but we have preferred, for the most part, to ignore them. But the combined influences of expanding communications, the inexorable growth in the world population, and the realization of limits to world resources force us to think further and further ahead. To do this effectively, we must better understand the long term consequences of the actions we take today. This means improved understanding of the dynamics of our world and the technological relationship of one field of science to another. This text for the very first time attempts to bridge multidisciplinary gaps and bring to a common interface all known technology of well construction as it may be related to the recovery of precious underground water supplies as well as other subsurface minerals.

What is required, ultimately, is a new attitude. An attitude which reflects the perspective forced on man by facing his world from a quarter of a million miles away. A small brilliant blue and white jewel suspended in a very large, very black, very neutral universe. Of all the elements composing this cosmic scene, only man — the dominant life form on this small planet — cares. Now, slowly, the awareness dawning that in spite of the stupendous flows of energy and cataclysmic events in and among the stars, man is the predominant influence on his own future here on earth. The future is not only heavily committed to outer space but also to inner space below the earth's surface where latent resources must be captured and conserved. So much of the earth's surface has been desecrated, polluted, and misused that if we are to survive, greater care and increased knowledge must be brought to bear on our subsurface resources of which water heads the list. Failure in this last arena of the struggle to live with nature will surely reduce the quality of our life to an intolerable level; thus, the importance of this book which addresses itself squarely to the increased but orderly development of our underground water resources cannot be stressed too highly.

Some of the future centuries may well be written in the stars but most of the immediate future is, rest assured, written within our own planet. I am sure that the future will welcome us; I am also sure, alternatively, that we will not be missed. Perhaps Archibald MacLeish painted the most vivid picture of our situation in his essay for the *New York Times*, December 25, 1968. People were still reflecting on the Christmas Eve message from Apollo 8 as it circled the moon, when they read:

> "To see the earth as it truly is, small and blue and beautiful in that eternal silence where it floats, is to see ourselves as riders on the earth together brothers on that bright loveliness in the eternal cold — brothers who know now they are truly brothers."

Russell L. Schweickart
Astronaut, Apollo 9
National Aeronautics
& Space Administration
Houston, Texas

1
Introduction

As society demands larger and larger quantities of fresh, potable water, the utilization of one of its natural resources, ground water, will become vitally important to the individual, to the municipality, and to industry. Today, ground water resources, which constitute more than 95 percent of the world's total fresh water supply, are essentially uncontaminated in contrast to the growing polluted nature of many of its surface water sources. It is clear that greater utilization of ground water will be made in the future since at present only about 20 percent of the water being used in the United States comes from underground. Ground water, as an abundant natural resource, is a relatively inexpensive, drought-proof, fresh water supply.

Since ground water is part of an unseen system which is relatively difficult to study directly and, therefore, difficult for the general public to understand, early protection and conservation of ground water is a necessity if this fresh water source is to remain unpolluted. Likewise unseen is the apparatus which brings underground water to the surface — namely, water wells.[68,170] A detailed understanding of well construction technology is, therefore, of paramount importance to assure the protection of the ground water resource.[73] Furthermore, with the growing emphasis on ground water usage, more efficient and sanitary well construction methods must be sought if future generations are to have potable water in sufficient quantities at reasonable costs. Some ground water pollution has already begun in parts of the United States,[201, 202] but wide-spread contamination caused by faulty well construction can be abated if rationally and technologically sound well construction methods are applied.[343] This can only be accomplished by rigid application of the best available technology and by continuing research and development.

PURPOSE AND OBJECTIVES

Over the past five years, national concern has been focused on the problem of pollution of all our natural resources. A state-of-the-art review of water well construction technology is particularly timely now, during the early stages of this general awareness, while ground water pollution control is being sought by various stete and federal agencies and by other workers in the ground water field within the United States. This new public awareness is felt in the areas of communication media, state and federal regulations, and the political arenas. Ground water, one of our most precious and irreplaceable resources, is naturally under scrutiny as well.

The primary purpose of this text is to review the current well construction methods and techniques presently in operation in the petroleum, mining, and ground water industries. The literature of these and related industries is voluminous, widely scattered, and contains various levels of applicability to water well construction technology.

A second objective of the investigation which brought this text into existence is to build an avenue of communication between the various industries and a central data collection organization in order to foster a more rapid transmission of technology in the future, which heretofore has been slow at best. Because the petroleum and mining industries have been highly efficient for many years in obtaining their goals of locating and developing oil and other high value minerals, their technology has reached elevated levels of sophistication. One of the first questions which might logically be raised here concerns the economic practicability of the many oil and mining field techniques treated in this text. It is obvious that the economic impetus of drilling for oil and of developing mining properties is different than that of drilling for water, but the difference in the order of magnitude is relatively small. However, sophistication of operations does not necessarily imply that these operations would be too expensive for the ground water industry because many oil and mining techniques have now been simplified, assimilated, modified, and put into field use by the ground water industry. The results have been technically successful, and the costs, unquestionably justified. As the quest for ground water continues further into the 1970's, the depths of water wells and their numbers will certainly increase.[70, 440] Water wells 1,500 to 4,000 feet in depth are not uncommon today and will become more widespread in the foreseeable future, especially in the irrigation regions of the western United States; the most advanced and efficient technology must be available in the years ahead to assure ground water protection and conservation.[490] State regulations and public health aspects of well construction practices will also come under increased pressure for appropriate revision.[152, 501]

The principles of operation and the concepts behind the petroleum and mining industries' techniques are examined in this text for possible reapplication. The ground water industry will, in the years to come, further modify these principles according to their needs if the techniques find practical use in the field. The industry is becoming well endowed with technical personnel to translate these new methods into practical field use, and with economic support, the rigid application of existing valid techniques can be promoted.

Another important purpose of this investigation is to provide computerized literature data for the U.S. Department of Interior's Office of Water Resources Research (OWRR), Water Resources Scientific Information Center (WRSIC) in Washington, D.C. The data-handling capabilities and the personnel who operate this agency are, without question, largely responsible for the growing technical awareness and the increased communication within the water resources field. Since the overt economic impetus was not inherent in the ground water industry, the U.S. Government has wisely provided the necessary economic and technical guidance.

This text is based on a review of a multitude of publications. After selected publications were abstracted, referenced, and key words chosen, the information was prepared as quick-retrieval, computer data input for inclusion in the data handling system of WRSIC and its twice-monthly publication: *Selected Water Resources Abstracts*.

APPROACH

During the initial literature search for this text, thousands of petroleum, mining, and water resource publications, reports, and technical papers were evaluated for possible applicability to the state-of-the-art of water well construction technology. Numerous trips to various centers of technology in the petroleum and mining fields were made by the senior author. Various academic and industrial institutions and organizations were visited during the early stages of the investigation in the hope of setting up avenues of communication for later information input into the National Water Well Association's Research Facility, the center for this investigation.

The response from the petroleum and mining industries was encouraging. Many of the industrial organizations were found to be most interested in the water well drilling market which is, at present, of relatively minor importance with respect to prime marketing objectives, i.e., oil and mineral exploration.[385]

The technical literature originates from publications in the numerous trade organizations, technical societies, and a few university centers which carry on petroleum and mining research. In order to reduce the time required for the literature search as much as possible, various petroleum information services were used for the initial review. Approximately 120,000 abstracts from the University of Tulsa's *Petroleum Abstracts* were reviewed for publications of applicability to this particular investigation. The initial search was conducted via microfilm cartridges and a reader-printer console. Each abstract selected was integrated into a card-file system for future, detailed review. After considerable discussions with numerous representatives of the major petroleum companies, related service organizations, and equipment manufacturers, it became clear that at least 60 percent of the technical data sought for this part of the investigation could be obtained by relying heavily on the University of Tulsa's Department of Information Services. This information service center, the largest of its kind in the world, began operations during 1961, financially supported by the major petroleum companies. In order to review the field's literature prior to 1961 as well as the assumed forty percent portion of the literature beyond the coverage of the primary information service, other library services and indexes were utilized.

The following major information services and libraries were employed during the course of this investigation:

(1) The University of Tulsa, Department of Information Services Tulsa, Oklahoma
(2) Rice University Houston, Texas
(3) Colorado School of Mines Golden, Colorado
(4) University of Minnesota Minneapolis, Minnesota
(5) Pennsylvania State University University Park, Pennsylvania
(6) Engineering Index
(7) Applied Science & Technology Index
(8) NWWA Research Facility Columbus, Ohio
(9) Ohio State University Columbus, Ohio
(10) Illinois State Water Survey Urbana, Illinois

The literature of the mining field is dispersed more than that of the petroleum field, primarily because a comprehensive information service is not available to the mining and mineral exploration industry. Therefore, technical information was sought directly from the various major academic centers of applied research in mining and mineral exploration within the United States and abroad. These extensive university libraries were searched for publications of possible applicability, and the investigation was given extensive assistance by numerous faculty members of these universities, without whose help the literature search would have been overwhelming. The references found to be of possible interest were cataloged in the master card-file system for later review.

The literature relating directly to water well construction technology is by far the most scattered of the three industries under consideration. Furthermore, a widely accepted central information service does not exist at present, as in the petroleum industry, nor are there academic centers where well construction techniques are treated in any continuing program of applied research. The literature on well construction technology is collected only by a few water well service and equipment companies, by numerous state and federal government agencies, as well as by the NWWA's Research Facility and other professional and industrial organizations. Usually, only selected aspects of well construction technology are of interest to the above companies, agencies, and organizations.

A variety of workers in the United States, Australia, and Europe were associated with this investigation and have contributed to the literature search of the ground water industry for information covering the broad interdisciplinary topic of well construction technology. An extensive literature search was conducted of the major publications found to generally offer pertinent papers or reports on the subject areas. The references and papers of interest were integrated into the master card-file system for later subdivision, review, and evaluation.

After the initial information input system for the petroleum, mining, and ground water industries was developed, a detailed review of approximately 2,000 potentially pertinent publications was undertaken. The master card-file was originally subdivided into general subject areas, within which additional topic subdivisions were later made to facilitate access to specific areas within the technology of well construction. Final selections were based on the degree of relevancy of each paper to the topic areas under consideration. The primary selections were reviewed in detail for the preparation of this text and were prepared for input to WRSIC data banks.

During the early stages of the preparation of this text, numerous decisions had to be made concerning the text's technical approach.[192] After considerable discussions with a host of technical personnel, industrial representatives, and the primary research staff of this investigation, the approach toward the preparation of this text was defined as follows:

(1) All state-of-the-art reviews of current technology should deal with the technology which in the forseeable future will be in general use in the specific industry of interest.

(2) Since the technology of the water well industry has, to an extent, resulted from modifications of principles originating in the petroleum and mining fields during the past 25 or more years, it was deemed advisable to define and then to explore the present technological principles and features of water well construction. Because the water well industry has never had the benefit of the historically close association of the driller and the well-site geologist found in the petroleum and mining industries, this loss of technical supervision must be replaced with a detailed explanation of technology that can be implemented in further advancement of water well construction techniques.[364, 579]

(3) It was deemed advisable to stress the principles of the current and new technology rather than to describe the physical appearance of current and new equipment incorporating such principles; therefore, the text's usefulness will extend beyond the equipment's obsolescence.[395]

(4) It was also deemed advisable to emphasize the results of the literature sources rather than to explore the merits of the numerous approaches without detailed field research which this text will hopefully stimulate.

DEFINITIONS

Water well construction technology has been defined for this investigation to include all technological features which relate to drilling, completing, developing, and maintaining water wells of various capacities for a variety of large and small domestic and industrial purposes in both consolidated and unconsolidated formations. It is assumed that the reader has a basic understanding of the technical field principles and concepts of well construction so as to reduce the extent of introductory material necessary for topic treatment. Furthermore, an annotated bibliography is provided should additional follow-up information be sought for the subjects treated.

To facilitate coverage of the various aspects which constitute well construction technology, the following broad topic subdivisions were incorporated in this text.

Research and Application of Well Drilling Technology
Research and Application of Well Completion/Development Technology
Research and Application of Well Maintenance Technology

Numerous factors must be considered in well construction, all of which bear heavily on the techniques of drilling. Rock characteristics play an important part, for example, in the selection of the most economical and efficient bit. In order to drill a well efficiently, a thorough knowledge of what happens on the bottom of the hole, as well as on the hole wall above is of vital importance. Rock drillability as explored in this text treats the laboratory and field achievements in technology as to the nature of the physical breakdown of rock in response to drilling variables, e.g., rock type, bit design, etc. The relationship of rock drillability and rock characteristics is explored with respect to penetration rate, rotary speed, bit wear, and other related variables.

The drilling fluid system is also examined in detail since it cools the bit, promotes bit longevity, conveys the cuttings away from the bit face to the surface for examination, plugs lost circulation zones, and promotes hole stability. These and other related factors are at present of top priority in drilling research and will, therefore, be treated in detail. In order to consider these new techniques and concepts, however, current drilling methods must also be explored to achieve an understanding of the relationship between the new concepts and the present stage of advancement of well drilling technology. The concepts in rock excavation, or drilling, will also be included to demonstrate new directions the industry may take in the not-too-distant future should a particular method prove to be of special merit.

Drilling either for oil, minerals, or ground water stands as one of the last remaining arts in an industry where virtually all other related operations have been translated into a science. The industry is now passing through a transition period which will elevate the art of drilling and herald the beginning of new drilling methods where drilling variables are more easily and reliably predictable.

The petroleum industry is well on its way toward making the drilling process a matter of controlled variables and predictable results. The mining industry has begun to look to this approach, although the magnitude of this industry's drilling parameters is more diverse and perhaps more difficult to define than those of the petroleum industry (within 2,000 feet or so of tbe surface, igneous, and metamorphic rock are drilled more frequently than common types of sedimentary rock). The mining industry drills under less severe hole conditions, e.g., less depth, less pressure, etc., but under relatively more severe economic pressure. However, the water well industry must drill under the strongest economic pressure; the industry at present cannot afford millions of dollars in researcb to control its own partially unique drilling variables. Although with increased technological transfer from the petroleum and mining industries, the water well construction industry will be able to control the variables which the petroleum industry and others have already defined. All variables lie within a system wbich has been defined for the water well industry but awaits further definition and industrial development.

Well completion or development is also composed of various systematic tecbniques. These techniques, such as cementing, aquifer stimulation, acidizing, blasting, well screen selection and placement, well logging, etc., are on the whole within the broad category defined herein as well completion. These techniques are interrelated, but should one system not be understood, well completion would not be fully acceptable nor would the well operate at designed efficiency. Any waste in these operations which is not anticipated is due to faulty techniques or to the lack of pertinent technology or perhaps, to a lack of a full consideration of the relationships between the technical systems involved.

A rapid advancement has occurred in recent years in the area of well completion and development. This text will treat in some detail the current techniques and the modifications or new concepts which have come from the petroleum and mining industries that are likely to find application in water well construction in the years ahead.

Water well maintenance is, in many instances, considered well rehabilitation. Maintenance also includes the various features which affect well life. Considerable work has been done by the petroleum industry and others on downhole maintenance procedures, cathodic protection, bacterial and chemical corrosion, etc. Aquifer stimulation is treated in conjunction with other "work-over" techniques.

The water well industry, as well as the petroleum industry, loses many thousands of dollars each year to "corrosion." It affects the well casings, the well screens, and the quality of the ground water produced by the well. Long term well performance depends not only on the design and construction techniques used but also on factors continuing after the well has been completed. The nature of the casing, the well screen, the pump, the aquifer characteristics, and the original ground water quality all play a vital role in determining the longevity of the well. The petroleum and water well industries have begun to deal with these problems. This text will explore the current practices and the new concepts which are in the process of adaptation by the water well industry. The oil industry's knowledge of maintenance problems has increased sharply in recent years. These problems differ considerably from those encountered in drilling operations. Not only have maintenance systems been defined, but many variables have been controlled in the well-maintenance field. Corrosion-incrustation systems, for example, have been examined in detail during the past 15 years, and the technology is available now to effectively reduce well failure due to "corrosion," if the economics merit such considerations.

In many cases, various topics are discussed briefly and then referenced as fully as possible for further study. The major factors of well construction technology are treated, however, in sufficient detail to delineate the techniques and problems as well as the benefits to be derived by the ground water and mineral exploration industries and the limitations involved from close contact and cooperation with the other extractive industries, i.e., petroleum and mining, etc.

The scientific aspects of ground water exploration are placed in proper perspective by considering ground water as a highly valuable mineral (to the public) as are other economic minerals (to company shareholders). All ground water geologists, hydrologists, mineral exploration geologists, oil geologists and engineers, government geologists and engineers, ground water planners, geology and engineering students, as well as drilling contractors and related vocational personnel, will more clearly understand the value of ground water when it is treated as an important natural resource consistent with other members of the family of economic geology.

The authors hope that after reading this text the oil geologist will have a more realistic respect for the upper 2000 feet of the earth's crust, the mineral geologist will be more clearly aware of his practical problems and of new tools available in his search for minerals, the government geologist and water resource planner will have a more realistic basis from which to educate and assist the public, the university researcher will expand his practical experience into the field and its problems, the drilling contractor will more clearly understand the problems of the professional workers and gain new respect for his responsibility in drilling and developing a very important natural resource, and finally, the university student who in the past has never known what to expect when he is asked to "sit on a well," interpret an electric log, or assist in any exploration program whether for ground water or for other minerals dealing with a drilling rig will more fully appreciate his duties.

2
Ground Water Pollution

Most recorded instances of ground water pollution have been fairly localized in extent and are of relatively low magnitude.[422] However, the increasing frequency of pollution occurrences now being recorded indicates that widespread contamination of aquifers may occur soon unless stringent precautionary measures are employed.[381, 382, 383]

In the past, dilution of liquid waste with large quantities of clean surface or ground water was commonly accepted as an adequate solution to pollution. This practice was successful as long as the quantity of pollutants was small in relation to the total volume of uncontaminated water available for dilution. The time is rapidly approaching when this solution will not be possible.[646] The total flow of some streams is already being used and reused several times, and with each use increased mineralization, heat or bacterial accumulation occurs. In many areas the clean water sources formerly used for dilution are now also polluted and in need of treatment before they can be classified as acceptable.

Ground water contamination caused by the disposal of solid waste in pits or land fills is already a very serious problem in some areas.[202] Chemical and thermal pollution caused by liquid waste disposal in pits or surface depressions also is increasing in some of the more heavily developed shallow aquifers. It is imperative that other methods of solid and liquid waste disposal be devised, perfected, and used. Until this is done, rigorous control of waste disposal site selection, operation, and maintenance must be employed to prevent serious contamination of ground water reservoirs.[434]

Domestic and farm water supplies are derived primarily from wells tapping shallow aquifers that have a high contamination potential. It is apparent that localized parts of these aquifers are already being seriously polluted, primarily with liquid waste derived from feedlots or poorly constructed or designed septic tank sewage disposal systems, and that many improperly constructed or poorly located wells in these areas act as conduits for vertical migration of contaminants into ground water aquifers.[340] Unfortunately, water samples from such wells are not analyzed on a regular basis, and the possibility of contamination often is not discovered until a high degree of contamination is present. A large percentage of the presently unaffected domestic and farm ground water supplies is in danger of serious contamination, unless proper disposal facilities for human and farm animal waste are provided and proper well construction practices are followed vigorously.

POLLUTION POTENTIAL

It is clear that a practical method of defining areas of potential ground water contamination is needed. In such areas various well design features can be considered on the basis of a well's possible role in contributing to local ground water pollution. Awareness of the pollution potential could serve to emphasize the necessity of technologically sound well-construction practices.

One such "early warning" method of potential ground water contamination has been explored by Walker.[645] He defines *pollution* as "an impairment of water quality by chemicals, heat, or bacteria to a degree that does not necessarily create an actual public health hazard, but that does adversely affect such waters for normal domestic, farm, municipal, or industrial use. The term *contamination* denotes impairment of water quality by chemical or bacterial pollution to a degree that creates an actual hazard to public health . . . ."

As an example of the above approach, Figures 1 and 2 roughly outline areas in Illinois where there may be danger of aquifer pollution now or in the future. The maps were prepared from the type of information that is typically available in most of the United States and elsewhere in the world. Using bedrock surface (outcrop) maps and surficial geological maps, the figures show areas where unconsolidated and bedrock aquifers *may* be subject to high,

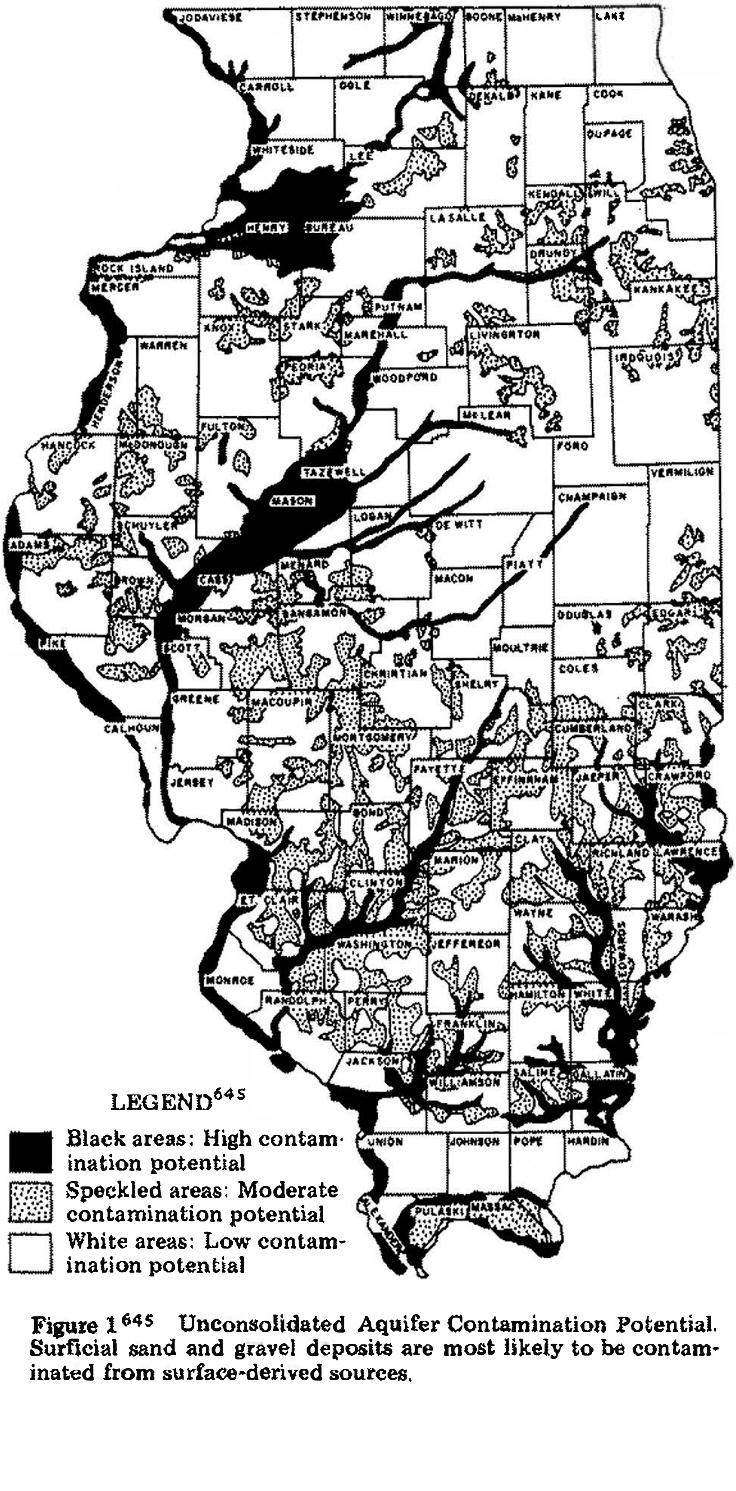


Figure 1[645] Unconsolidated Aquifer Contamination Potential. Surficial sand and gravel deposits are most likely to be contaminated from surface-derived sources.

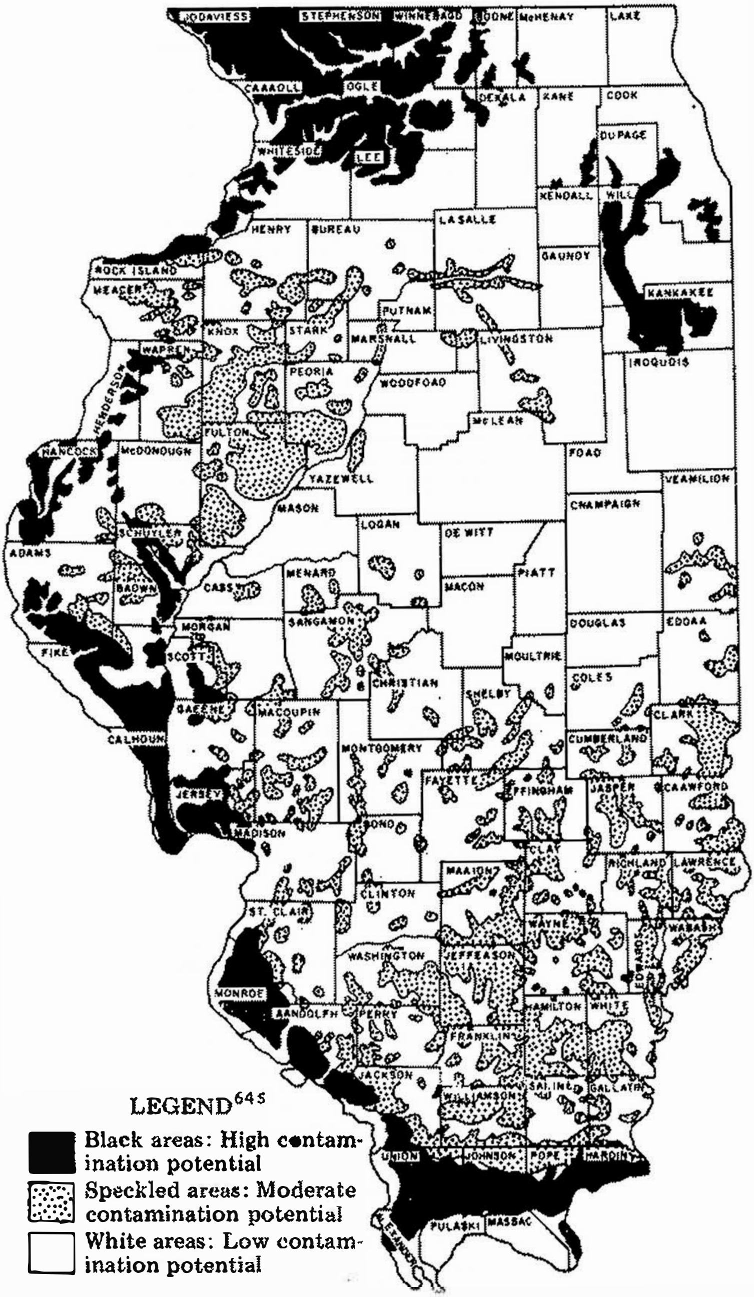


Figure 2[645] **Bedrock Aquifer Contamination Potential. Outcrop areas of creviced dolomite and limestone aquifers have a high contamination potential.**

moderate, or low contamination potential. The maps serve as a guide in selecting reasonably safe areas for locating productive wells or waste disposal sites. Of course, only the general parameters can be established, and local field information should accompany any follow-up.

Shallow aquifers that intersect or lie near ground level readily receive, store, and transmit possible contaminants down gradient from points of entry to natural discharge areas or nearby pumping centers. Deeply buried water-bearing units overlain by relatively impermeable shale or clay beds are generally effectively sealed from the surface. These units must receive most of their recharge from outcrop areas of the aquifers.

Deeply buried parts of aquifers may be relatively free of contamination derived from surface sources, providing wells and test holes tapping these units are properly sealed. In the outcrop areas, however, waterborne contamination can directly enter exposed or thinly covered, weathered, or creviced limestone and dolomite beds, faults, etc., through interconnecting systems. Surface derived contaminants gain easy access to shallow sandstone or sand and gravel formations through interconnected uncemented pore spaces.

Outcrop areas of the aquifers are the primary controls used to delineate areas of high, moderate, and low contamination potential shown on the maps in Figures 1 and 2. Other information used include: drillers' logs, records of wells, chemical analyses of water samples, temperature data, and recorded case histories of heat, chemical, and bacterial pollution from the files of the local water survey, public health department, and geological survey.

Unconsolidated aquifers subjected to a high contamination potential (Figure 1) generally are contained within those areas covered with glacial drift or outwash deposits. The surfical aquifers usually consist of very permeable sand and gravel capable of producing from about 100 to more than 500 gpm for properly constructed wells.

The areas of moderate contamination potential roughly coincide with those parts of Illinois, for example, covered only by glacial deposits. Water-bearing formations in these areas are generally thinner and less permeable than those of glacial deposits, and wells capable of producing in excess of 20 gpm are rare.

Areas having a low contamination potential are either underlain by deeply buried sand and gravel aquifers, isolated from the surface by relatively impermeable clayey deposits, or the unconsolidated materials present are thin and non-waterbearing. In parts of Illinois, for example, properly constructed and cased wells effectively seal deep aquifers from surface-derived contaminants.

Bedrock aquifers subject to a high contamination potential generally are creviced formations, shallow carbonate formations and are most likely to be contamined from surfaced-derived sources (see Figure 2). Areas of moderate contamination potential are underlain by shale, sandstone, and limestone formations. Also, highly mineralized water from deeper buried parts of the aquifers may be obtained from shallow wells. Low contamination potential bedrock aquifers normally are isolated from land surface by thick glacial till or bedrock shale formations.

The above approach, although developed for the state of Illinois, is directly applicable to other regions of the United States, in addition to areas outside the United States where the necessary hydrogeological data are available. The approach is especially applicable in areas of relatively high rural population density or in areas with a high projected agricultural or industrial expansion rate.

Ground water in urban and other areas of concentrated usage is subject to contamination from a number of sources.[294] Walker[645] and Deutsch[202] cite typical examples of "natural" contamination/pollution. Figure 3 illustrates a commonly encountered case of ground water quality deterioration caused by leachates from the city dump and the probable manner of entry and movement of chemical contamination from this source to the municipal well field. Interception and diversion of contamination by cones of influence of the nearby municipal production wells apparently began almost immediately after pumping started, as evidenced by the progressively increasing total hardness, sulfate, and chloride content of ground water withdrawn from this field.

Contaminants can enter the well as it is being drilled, during its operational life, or following its abandonment.[54] Because of this

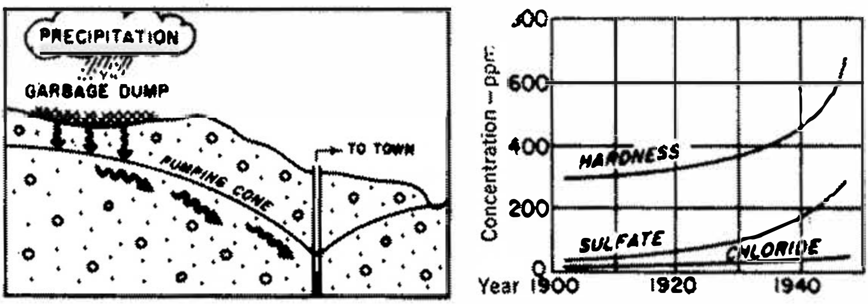


Figure 3[645] Typical ground water quality deterioration from surface waste disposal operation.

complex environment, such contamination is often difficult to rectify; however, Ham[300] summarizes the salient features of potential ground water contamination of water wells and delineates many of the problems encountered.

During the drilling of a well, a hole is opened (and sometimes cased) from the ground surface into the aquifer. Various substances, including water, drilling fluids, muds, chemical additives, hay, gasoline, etc., are, on occasion, introduced into the well to facilitate drilling and development. The volume of these materials is generally small compared to the volume of the aquifer. In essence, they are "one-shot" additions. If the well is promptly completed and test-pumped, most of the substances added during drilling are drawn back into the well and removed. However, under atypical conditions (including the presence of cavernous rock) highly permeable gravels or other conduit-like aquifers, such drilling materials may move too far from the well to be recovered and may contaminate nearby wells.

However, a special problem present during drilling is the danger of accidental entrance of flood waters or concentrated chemical/radioactive fluids into the well. Any uncompleted or unsealed well in proximity of a surface stream or stored toxic fluids is a potential avenue for contamination. A comprehensive review of the practical aspects of ground water pollution has been published which explores the numerous features of potential pollution of the ground water resource.[86]

Possibly of greater potential consequence is the introduction of biological agents into the aquifer via drilling muds or other materials. The presence of sulphate-reducing and other similar non-disease-causing bacteria in wells can be attributed to contamination of drilling fluids, muds, etc., introduced during the drilling process. Little information is available on the effects of this procedure; however, the method of bacterial introduction may well be an important contributor to later contamination of aquifers via the growth of specific types of corrosion/incrustation-causing bacteria in wells coupled with favorable local ground water chemistry, temperature, etc.[99,146,492]

The presence and severity of both chemical and biological contamination of the well during its operational life and post-abandonment period are closely related to well design, location, and construction. With respect to bacterial contamination causing human diseases, it has been established that contaminated surface water has entered a well either because of faulty well construction methods by transmission from some distant point through the aquifer (especially in creviced rock), or from sewage or other wastes that have been improperly disposed.[362,481,527,533] Proper well location based on a firm knowledge of the local geological condition can minimize the potential problem.[434]

WELL STRUCTURE

The well structure, however, offers another avenue for contamination. Any break or other opening in the casing or between the casing and the pump base or seal is a potential source of contamination (see Figure 4-A). Also, the discharge system offers opportunity for reversal of flow (see Figure 4-B).

Aside from the well structure, the disturbed zone immediately surrounding the casing frequently offers a passage for contaminants (see Figure 4-C). The presence of an improperly constructed gravel pack may also lead to contamination because of the necessity for maintaining a conduit from the surface into the well for installation

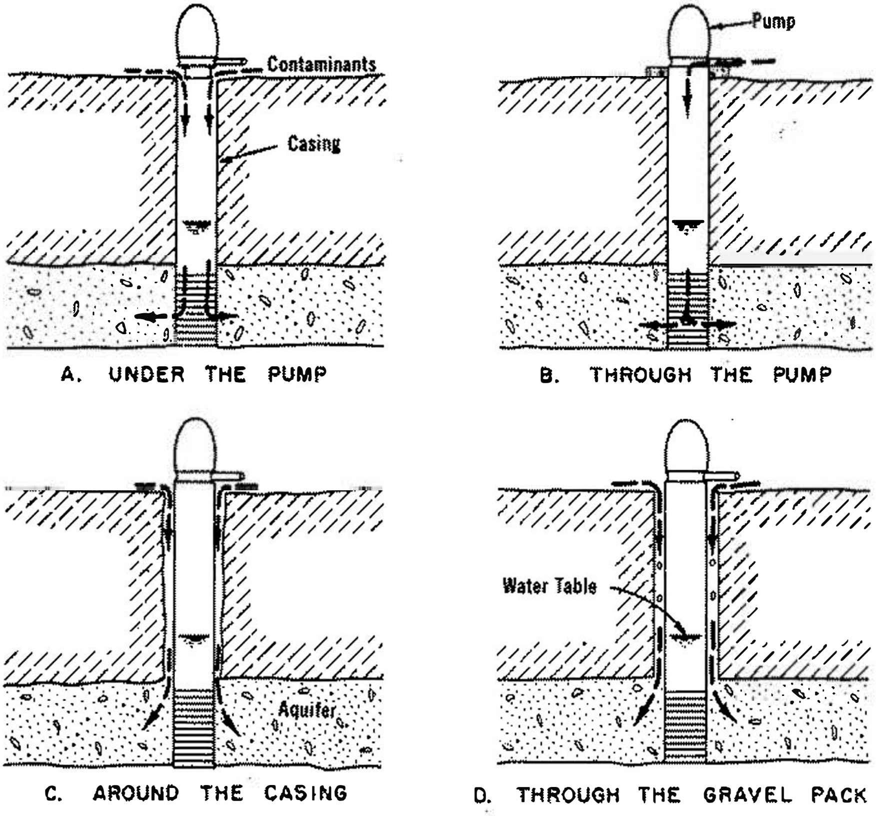


Figure 4[300] Entrance of contaminants.

of the pack. In some examples of poor construction, the pack is continuous from the bottom to the surface without any method of sealing at the surface (see Figure 4-D).

The more advanced of the techniques presently used for preventing contaminants from entering around the casing and through the gravel pack are adequate under normal conditions. However, changing physical conditions of the well which often result from improper design, construction, operation, or lack of maintenance, in time tend to negate protective techniques no matter how sound in principle. These include:

(1) Subsidence, due to sand pumping, resulting in surface-grade reversals, destruction of surface protection, and reduction in the effectiveness of the cement-grout seal (see Figure 5).
(2) Desiccation or other factors causing shrinkage, cracking, or other alteration of grout or cementing material.
(3) Breaks or leaks in discharge pipes, leading to the failure of sanitary protection apparatus.

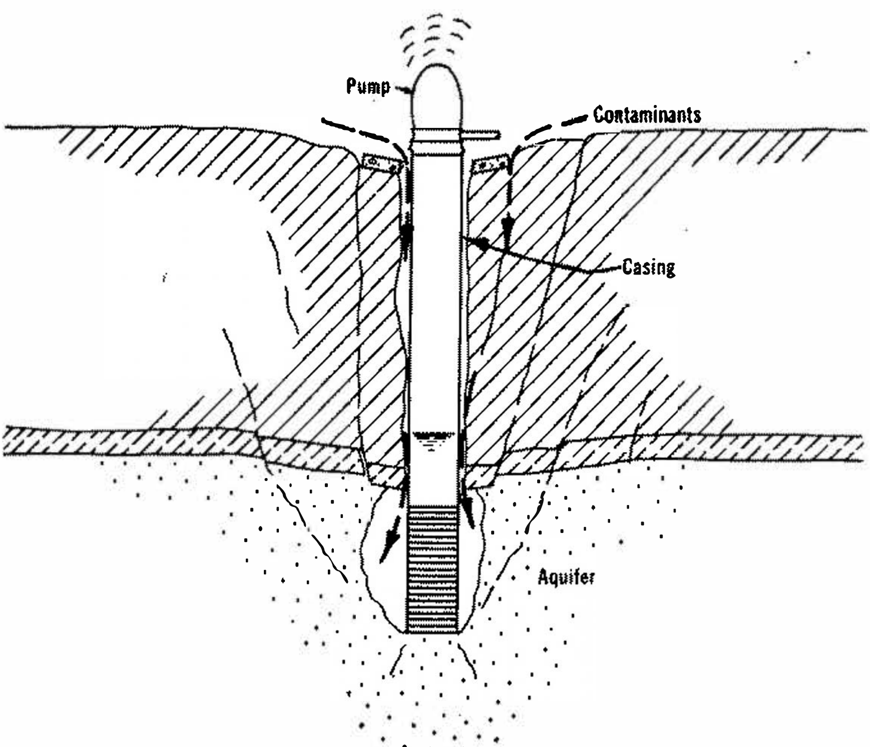


Figure 5[300] Entrance of contaminants resulting from subsidence.

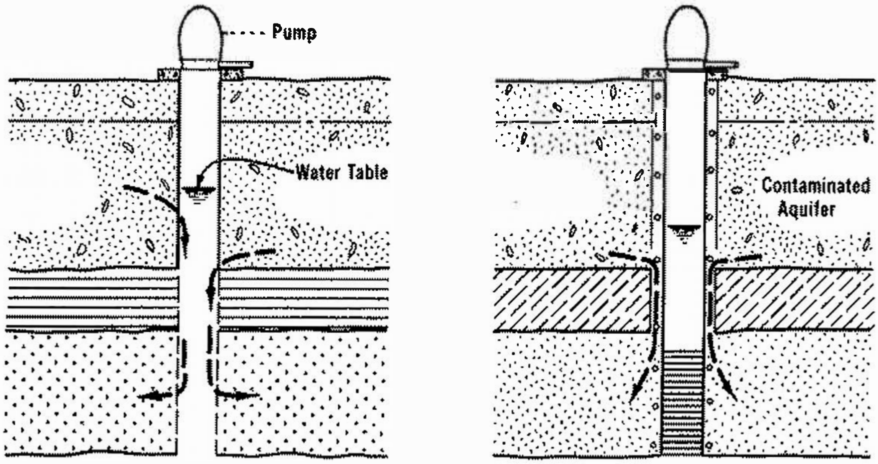
Jones,[340] in a case study on well construction and water quality, reports that wells lacking adequate sanitary protection from improper well construction methods serve as uncontrolled ground water recharge points. He further states that, with the entrance of contaminated surface water into a well, the ground water quality deteriorates. This deteriorated ground water is often equated, by random water well samples, with ground water quality when, in fact, the contamination resulted from the entering surface water. Poorly constructed wells may ruin high quality ground water. This becomes critical when a well receiving dissolved solids from livestock wastes, agricultural chemicals, or fecal organisms from surface drainage becomes a source of ground water. The recent study by Jones [340] substantiates this possibility and suggests that improper sanitary protection of wells incorporating inadequate well-construction methods requires an early solution, especially with respect to locating such well defects *after* well construction has been completed.

When a well penetrates a single, relatively homogenous aquifer under water-table conditions, the possibility of contamination originating from anywhere but surface sources is remote. However, the penetration of two or more aquifers each under a different hydraulic head presents an entirely different situation. The well bore or gravel pack can act as a vertical conduit for natural flow from one aquifer to another. One aquifer may become contaiminated by water from another aquifer, although the two are separated by an appreciable thickness of impermeable material (see Figure 6).

When chemically unsuitable water is encountered during drilling, the contributing zone normally is sealed off with casing, liner, cement grout, or is totally plugged back. However, the presence of bacterial or other organic contaminants is not as readily detectable.

A potentially serious situation exists when a well is cased through a contaminated near-surface aquifer and completed in a deeper aquifer. Under favorable head differentials, contaminated near-surface ground water can enter any opening in the casing and be conveyed into the aquifer in use (see Figure 7-A). The opening may be a split seam, improper weld, joint failure, corrosion pitting, or inadequate seal below the casing shoe. The extension of an inadequately protected gravel pack upward into a near-surface aquifer can lead to downward drainage of contaminated water into the lower-lying aquifer (see Figure 7-B).

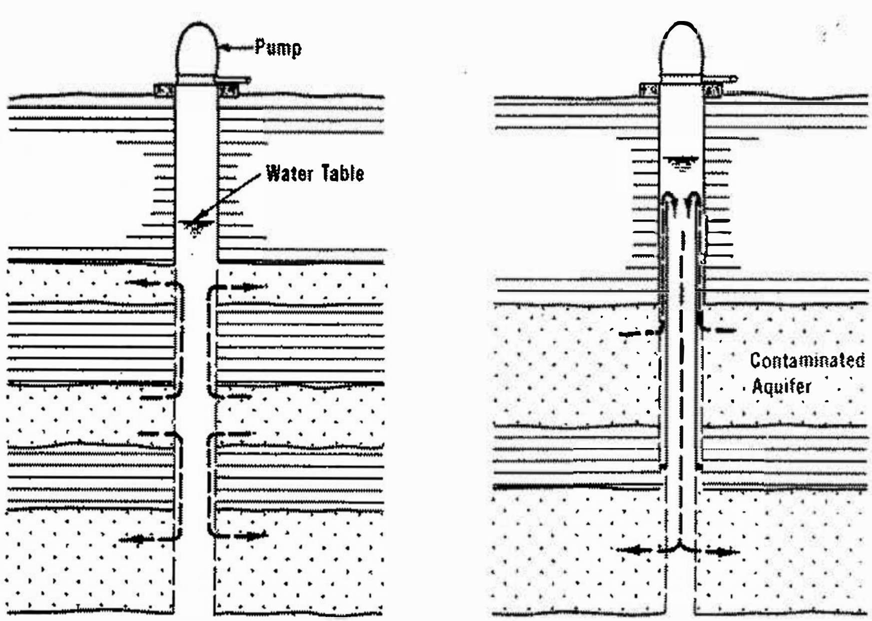
Disuse of a water well creates conditions that often lead to an increased potential for contamination and accelerates deterioration as in other metallic structures. Upon abandonment, the pump should



A. THROUGH THE CASING

B. INTO THE GRAVEL PACK

Figure 6 300 Entrance of contaminants.



A. BY VERTICAL FLOW

B. BY VERTICAL FLOW BY-PASSING A LINER

Figure 7 300 Entrance of contaminants.

be removed and an attempt made to insure that the well does not constitute a public hazard. Common abandonment procedures often are less than ideal. The contamination present during the operational life of a well usually will continue after abandonment unless preventive measures are taken.

An abandoned well is a convenient receptacle for disposal of wastes, or it may become a haven for vermin. There are numerous cases of building activities uncovering old, unprotected, and unrecorded wells.

The presence of unrecorded wells abandoned in areas subject to natural flooding or in permanently flooded areas, such as new reservoirs, introduces unnoticed surface water into fresh water aquifers. The addition of reservoir operating head can cause high inflows with the attendant danger of continuous ground water contamination.

The surface contamination hazards associated with abandoned wells usually are obvious and can be rectified without great difficulty. However, subsurface contamination is more insidious, difficult to detect, and often expensive to control especially if the well has undergone deterioration. The corrosion of well casing and liners, originally installed to seal off contaminated aquifers, constitutes a major hazard if head differentials in the various aquifers are favorable for interflow between aquifers.

Of practical concern are wells that penetrate saline or other similar aquifers having high artesian heads. Normally, such aquifers are sealed off to permit the production of usable water from other aquifers. After abandonment, deterioration can result in the well becoming a subsurface hydraulic conduit which continuously adds contaminants to a fresh water aquifer.

Concerning abandonment of wells, it is generally accepted that restoration of the controlling geological conditions that existed before the well was drilled or constructed should be attempted as far as possible.

Ham[300] and Jones[340] state that the potential for serious water well-induced contamination of ground water is always present and will become intensified with increased use of ground water and concentration of facilities, especially in areas with high-population growth rates. Once recognized, however, the problem is alleviated by appropriate statutory and administrative measures and by the development of new and improved materials, equipment, and techniques. Appropriate monitoring tools and techniques are also needed to assure the sanitary protection of the water well and the valuable ground water resource.

OIL WELLS

All wells, regardless of their use, pose a potential threat to the ground water environment. The part that oil and gas wells play in local ground water contamination has been well documented, but obviously neither oil/gas wells nor water wells will be prohibited in the foreseeable future since contamination is unnecessary and a result of inadequate well construction techniques and practices. However, unusual or poorly understood local geology and hydrology also contribute heavily to many types of ground water contamination.

Studies of well blowouts and possible development of communication between a fresh water aquifer and an oil-bearing sand have been made as have studies of possible ground water contamination related to poor oil production practices.[554,638] Brines produced with oil and gas are also known to contribute to ground water pollution,[184,267] and a universally satisfactory method for their disposal has not been found to date.[611,600] Some brines, however, contain valuable minerals that are economically recoverable, and treatment or disposal of such brines should be coordinated with mineral recovery processes whenever possible.[178]

Collins[179] cites several publications on oil field brine disposal by subsurface injection into permeable strata and describes gathering systems, pumps, treatment methods, and injection well construction techniques. Two recent symposiums, i.e., National Ground Water Quality Symposium[481] and the Underground Waste Management and Environmental Implications Symposium,[9] have dealt with major water quality problems and state-of-the-art of waste disposal techniques.

Disposal methods have been blamed as the possible cause of some earthquakes, and if a natural disaster such as an earthquake occurs, new faults or fractures in subsurface strata may provide an avenue between the strata containing the waste and the fresh water aquifer which obviously would be potentially disastrous to the potential usefulness of any ground water system involved.

PETROLEUM EXPLORATION AND PRODUCTION

When oil or gas wells are drilled into an abnormally high fluid-pressure environment, there is always the possibility of a blowout unless elaborate precautions are taken and proper drilling fluids are used.[179] This situation can develop, for example, if degradation or sloughing off around the casing in a high pressure zone occurs allowing the pressurized hydrocerbons to escape along the outside of the casing to an upper zone (see Figure 8).

Collins[179] stresses that most states have laws requiring the setting of surface casing to protect the fresh water aquifers from invasion by brines and hydrocarbons from deeper horizons. A minimum of two strings of casing—the surface casing and the oil-string casing—are usually used and are generally adequate. Additional strings of casing may be employed if heaving shales are found while drilling progresses, if abnormal pressures are encountered, or if a zone of lost circulation is encountered. Each additional string of casing, however, requires more capital and increases the cost of the well.

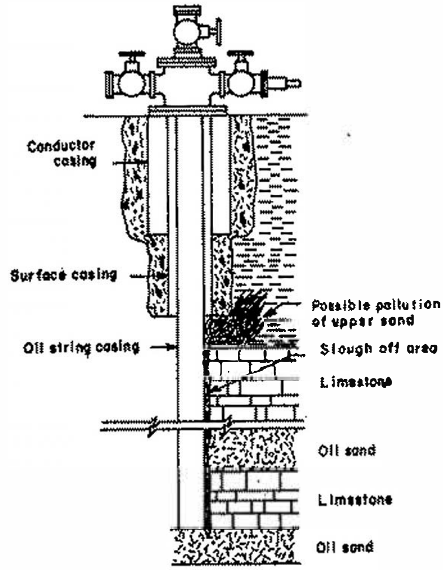


Figure 8 [179] Manner in which heaving shales or incompetent zones can slough off and allow a lower zone to communicate with an upper zone.

If appropriate precautions are not taken in planning, drilling, and completing an oil or gas well, serious consequences can occur. For example, during drilling operations, a well may blow out if adequate mud pressure is not maintained. Such a situation may develop if the mud line is accidentally broken or if the well casing is not properly cemented to competent zones. Figure 9 illustrates what may well occur if fluid from a high pressure well escapes into an incompetent zone and develops communication between a lower hydrocarbon-bearing horizon and an upper aquifer.

NATURAL GAS EXPLORATION AND PRODUCTION

Blowouts of natural gas wells have also contributed to ground water pollution and are especially serious if the natural gas contains appreciable quantities of hydrogen sulphide. Many gas wells contain enough hydrogen sulphide to contaminate fresh water upon contact. Such contact may develop if well construction methods are faulty and communication between the gas zone and an upper freshwater

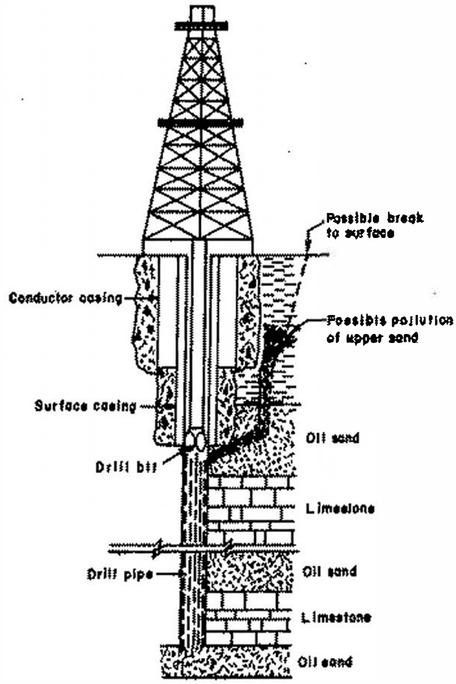


Figure 9[179] Probable manner whereby a well blowout can develop communication between an upper sand and a lower sand.

zone occurs. Brines associated with hydrogen-sulphide-bearing gas zones also contain appreciable quantities of the sulphide. Keech[345] cites a dramatic case history of widespread ground water contamination by a subsurface, natural gas blowout.

OIL FIELD BRINES

Waters associated with petroleum in subsurface formations usually contain many dissolved ions. Contamination of shallow ground water by the use of "evaporation pits" for the disposal of brines has been widespread. Such pits, although outlawed in some states, are still too often found in use because of the lack of energetic local enforcement. Salt water disposal through faulty disposal wells and increasing water flooding activities both pressurize lower formations and can result in the movement of brine up poorly plugged abandoned oil wells. Of course, this causes contamination of fresh water aquifers. Furthermore, sources of such contamination are difficult to trace.[660]

The stability of petroleum-associated brine is related to the constituents dissolved in it, to the chemical composition of the surrounding rocks and minerals, to the temperature, the pressure, and the composition of any gases in contact with the brine. Lehr[384] describes some of the consequences of local aquifer contamination by improper brine disposal methods. Commonly, evaporation pits facilitate both vertical and horizontal migration of oil field brines to the ground water reservoir, as a result of a surface-derived source of shallow aquifer contamination (see Figure 10).

ASSIMILATION OF TECHNOLOGY: A FINITE SOLUTION

The ground water industry must serve two masters or must seek two goals concurrently if it is to flourish in the years ahead. It must,

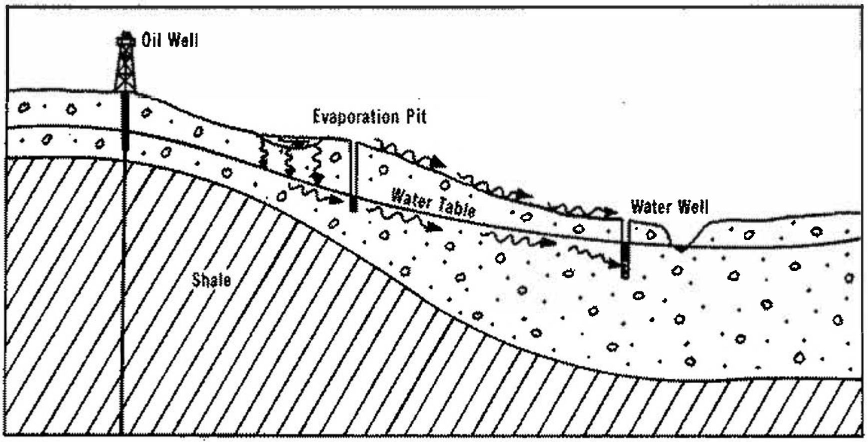


Figure 10[645] Contamination of ground water from brine disposal.

of course, make a reasonable profit, but it must also act as the day-to-day guardian of the ground water resource. This can be accomplisbed by incorporating the most up-to-date techniques of well construction, completion, and maintenance. The achievement of both goals, however, is not mutually exclusive, as any successful well contractor can testify. There is no tenable excuse for blatantly poor well construction or for inadequate profit in a healthy economy. Improved technology designed to increase profit also increases the quality of well construction and serves as the final answer to water well-induced contamination of the ground water resource.

Monitoring equipment is needed in the petroleum industry to continuously assure that all materials used in the construction of oil or gas wells remain as designed throughout the years of operation. Corrosion as a major cause of eventual ground water contamination is of serious concern to the petroleum industry as well as to the ground water industry. Furthermore, oil/gas well abandonment techniques bear heavily on potentially widespread ground water pollution. These techniques should be under continuous technological development, the most effective of which should be used consistently in the field as a matter for the common good, not as a matter of economics. Petroleum and potable water are not of equal importance to society's needs for there are energy-source substitutes for petroleum and related oil/gas products, e.g., uranium, geothermal[97, 605] and solar energy, etc.; but there is no known alternative for potable water. The development of petroleum and ground water is competitive only to the extent that the latter must be protected more jealously than the former. Both can be developed simultaneously if technology can serve to protect one from the other. Too often, strong industrial influences promote unfortunate compromises between the economic development of one resource over another.

Water well construction technology has developed considerably in the past 25 years. The impetus for such development has come from the inherently more wealthy oil and mining industries. New techniques and concepts have, for many years, been adapted by the water well construction industry after practical applications were realized by numerous service companies, equipment manufacturers, and technical personnel in the petroleum, mining, and ground water industries.[265]

The ground water industry, in recent years, has returned this assistance of the petroleum and mining industries by developing some of its own concepts and techniques which have found subsequent use in the petroleum and mining fields. Each industry is seeking more economical ways of developing the natural resources of the earth, e.g., petroleum, ground water (including geothermal resources), and other minerals of value which today's world must have in greater and greater quantities.

The U. S. Environment Protection Agency (EPA) in cooperation with the U. S. Office of Water Resources Research has recently published a three-part selected annotated bibliography on subsurface water pollution, i.e., Part I: Subsurface Waste Injection; Part II: Saline Water Intrusion; and Part III: Percolation from Subsurface Sources. These publications and others to be released soon represent the first major step in the wide-spread dissemination of research reports and studies of ground water pollution and contamination control efforts.

The assignment of responsibility for ground water pollution control is difficult because so many segments of society contribute to pollution. However, the primary responsibility can and should indeed be assigned to that segment of the industry contributing the greatest impact on pollution. The industries drilling for oil/gas, minerals, or ground water, who open the ground water reservoir to potential pollution, must design well construction technology and operations so that the risk of future pollution to the ground water reservoir is all but eliminated. To accomplish this, well construction should be based on pollution control factors rather than on economic factors which too often overshadow pollution control efforts.

The complaint is often heard that the well constructed in strict accord with the available technology is too expensive. What is too often not understood or not widely accepted is that if the efficiency of the various well construction operations were increased only slightly over present levels, the monetary savings derived would pay for well construction of the highest quality capable of meeting the strictest of well standards and specifications. So it behooves the drilling industry to look to technology for an answer to its very real economic problems. Strict standards and specifications are not designed to impoverish the drilling industry, only to assure the protection of one of the nation's most valuable natural resources.[674]

To accomplish the necessary increase in efficiency of many well construction operations, a more detailed appreciation of the principles of available technology must be realized if an economic edge on pollution control is to be accomplished in tbe near future. In the following chapters, various aspects of well construction are explored with an accent on increasing efficiency.

W.A. Pettyjohn has recently published another important contribution to surface and ground water quality control entitled: *Water Quality in a Stressed Environment*, (Burgess Publisbing Company, Minneapolis, 1972). In addition, W.J. Powell, *et al.*, have also made an important contribution in the form: "Water Problems Associated with Oil Production in Alabama," 1963, Geological Survey of Alabama, Circular 22.

3
Rock Drillability: A Review

The early bistory of water well drilling relates the ingenious beginning of drilling technology.[135,157] And today, the technical literature abounds in papers on the flow characteristics of ground water to wells, the relation of well diameter to capacity, the percent of open hole, the drawdown, and other factors relating to well geometry, discharge, and aquifer response.[248,632] The practical field relationship of rock drillability, however, has remained obscure.

Recently, not only have the tools become available to the shallow drilling industry, but also advanced drilling techniques have begun to find application in water well construction, although the transition has been slow. The broad features of water well technology have had many years to become established, but the accent today is on efficiency, and an acceleration of the adaptation process is mandatory. "Optimization of operations," a method of maximizing efficiency, has been an important concern of the oil industry for a number of years,[232] because more efficient drilling practices promote higher profits.[505]

One of the most important aspects of an information transfer from the oil industry is the concern for detail. If the oil industry's attention for detail can be empbasized in the shallow drilling industry, one effect could be a substantially increased level of efficiency in water well and mineral exploration drilling.

16
Annotated Bibliography

This annotated bibliography is keyed, where possible, to the computerized accession numbering index incorporated in *Selected Water Resources Abstracts*, a semimonthly publication of the Water Resources Scientific Information Center (WRSIC), Office of Water Resources Research, U. S. Dept. of the Interior.

1. Ackermann, W. C., 1969, "Cost of Pumping Water," *Ground Water*, Vol. 7, No. 1, January-February, pp. 38-39.

   Use of this material will assist in the determination of cost of pumping water, given the quantity of flow required, the total pumping head, the wire-to-water efficiency, and the unit cost of power. A table of conversions is presented to aid in reducing theoretical equations to simplified equations, and a figure is provided for graphical solutions of the equations. WRSIC #W71-09731

2. ________, 1969, "Cost of Wells and Pumps," *Ground Water*, Vol. 7, No. 1, January-February, pp. 35-37.

   The use of this material will give an estimate of the well and pump costs for projects requiring a given capacity, but it does not substitute for detailed engineering studies. Well cost data were analyzed for three categories according to the aquifer tapped: sand and gravel, shallow bedrock, or deep sandstone. WRSIC #W71-09730