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Hydraulics of Wells

Design, Construction, Testing, and Maintenance of Water Well Systems

Prepared by
the Task Committee on Hydraulics of Wells of the
Groundwater Hydrology Technical Committee of the
Groundwater Council and Watershed Council of
the Environmental and Water Resources Institute of the
American Society of Civil Engineers

Edited by
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A manual or report in this series consists of an orderly presentation of facts on a particular subject, supplemented by an analysis of limitations and applications of these facts. It contains information useful to average engineers in their everyday work, rather than the findings that may be useful only occasionally or rarely. It is not in any sense a "standard," however; nor is it so elementary or so conclusive as to provide a "rule of thumb" for nonengineers.

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In February 1962 (and revised in April 1982) the Board of Direction voted to establish

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CONTRIBUTORS

During the past few decades a large number of papers in the groundwater realm were presented at the annual conferences of the Hydraulics Division of the ASCE. From these presentations and resulting discussions, it became very clear that greater reliance is being placed on the extraction and utilization of groundwater resources for domestic and commercial water supplies. However, it also became apparent that there is no single document available in the market that addresses the problems facing the water well industry with regard to securing safe water supplies from groundwater resources and protection of water wells and pumping equipment. It was felt that design professionals were limited regarding reference material concerning the complete water well system design including the design of hydraulic parameters and deterioration caused by corrosion, incrustation, and poor maintenance. Also, there was a definite need for reliable information for repair and replacement of well materials and pumping equipment, as well as for testing procedures to design well discharge rates, total dynamic head, plant efficiency, and power parameters.

To achieve the desired objectives of worldwide economical supplies of groundwater, in August 1998 a Task Committee on Hydraulics of Wells of the future Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE) was formed under the stewardship of the parent Groundwater Hydrology Technical Committee. The following are the members of the Control Group of the Task Committee on Hydraulics of Wells.

Nazeer Ahmed, *Chair and Secretary*
Tom W. Anderson, *Vice Chair I*

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The primary objective of the newly formed task committee was to review current published data most pertinent to water wells and deep-well turbine pumps, as well as to develop a manual describing well design, construction, testing, operation, rehabilitation, and maintenance of water wells and pumping equipment. The functionality of the manual required development of a comprehensive technical reference focusing on waters-supply wells and pumping equipment. Potential users of this manual were considered to be engineers, hydrogeologists, consulting firms, public officials, private well owners, state and federal agencies, business communities, administrators, managers, municipal personnel, and colleges and universities.

Well hydraulics is a multidisciplinary field in modern human history and, therefore, a global search was launched to solicit experts in a number of areas associated with hydraulics of wells, such as agriculture, agricultural engineering, biology, chemistry, chemical engineering, civil engineering, electrical engineering, hydrogeology, geochemistry, geophysics, geology, geological engineering, mechanical engineering, metallurgical engineering, microbiology, plant pathology, and the like. The writers, reviewers, advisors, and benefactors who volunteered to serve on the newly formed Task Committee on Hydraulics of Wells, their names along with their degrees, areas of expertise, and nationalities are given as follows.

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An original table of contents comprising 19 chapters, based on the module concept, was prepared by Nazeer Ahmed for development of the manual. As the writing progressed, individual chapters were submitted to the corresponding reviewers for their comments. Through the collective review process, it was determined that each chapter was written as a stand-alone product and that there was a lot of overlap and duplication of material. Therefore, a concerted effort was made to reorganize the table of contents as it would appear in the manual as the final printed version. The revised contents consists of eight chapters and six appendices and was prepared through mutual consultation and joint efforts of J. Paul Riley, Calvin Clyde, Dennis Williams, Nazeer Ahmed, Conrad G. Keyes Jr., Bruce Jacobs, Otto J. Helweg, Tom W. Anderson, Earl Greene, and Bangalore Lakshman. The writing and review assignments of individual authors and reviewers are given as follows.

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PREFACE

Groundwater is a vital resource in cultures and climates of all countries around the world. In the United States, for example, approximately half of the nation's drinking water supply is derived from groundwater resources. Because of its relatively high quality and dependability, groundwater frequently is used for drinking water supply, and demand is expected to rise worldwide as populations expand and technologies progress to accommodate all current and anticipated future growth.

Reasons for reliance on groundwater are many, including the ubiquity of groundwater reserves, its high quality, and the relatively low level of infrastructure required for storage and transmission. Groundwater, although reliable and readily accessed, is not free from costs and limitations, however. Aging wells and pumping equipment, as well as storage and transmission infrastructure, must be maintained to preserve the function of the well, as well as the quality of water produced. Well capacity and water quality also may be threatened by a variety of physical, chemical, biological, and environmental factors, such as pollution, overdraft, or dry periods, to name a few. Although lost capacity may be regained through renovation of equipment and well rehabilitation, sometimes it also may prove less costly and more advantageous to install new wells. Further, considering the expected energy shortages coupled with high maintenance and operational expenses, it may become prohibitively expensive to utilize this natural resource in the future. It is, therefore, necessary by all means to refine standard practices in the water well industry continually in order to improve current technology and to evolve cost-effective methodologies for the identification, development, and procurement of groundwater resources in the future.

To focus on the development and management of worldwide economical supplies of groundwater, in August 1998 the Task Committee on Hydraulics of Wells of the future Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE) was assembled under the stewardship of the parent committee, the Groundwater Hydrology Technical Committee. Members of the Task Committee on the Hydraulics of Wells have contributed their expertise in various aspects of the water well industry to produce this international manual on hydraulics of wells. Also, it may be reiterated here that this manual was originally initiated, reviewed, and approved under the auspices of the then Watershed Council in charge. However, at a later date, it also was resubmitted for a fresher look and second review to the newly formed Groundwater Council. Additionally, all their review comments have been incorporated into the manual, and finally, it was approved by the Groundwater Council as well.

From the detailed contents of the manual, it is apparent that a large number of individuals have worked hard on its development and have provided useful technical information for the design professionals, state and federal executives, field supervisors, office managers, and private and corporate owners in the water well industry for public and private use and consumption. On behalf of EWRI–ASCE, I would like to thank all the authors, reviewers, advisors, Blue Ribbon Committee members, Watershed Council members, Groundwater Council members, ASCE Publications Committee members, EWRI Technical Executive Committee members, EWRI/ASCE editorial and technical staff members, and other private advisors, benefactors, and patrons for their enthusiasm, hard work, and professional contributions. They are the ones who have made the publication of this manual possible with their ingenuity, talents, sacrifices, experience, technical know-how, dedication, patience, perseverance, and kindness. Personally and professionally I am greatly indebted to all of them.

For future developments and improvements of the manual, please send your comments, recommendations, and published references to the Chair of the Task Committee on the Hydraulics of Wells. Thank you very kindly for your continued support and interest, as well as for all your selfless and zealous efforts.

Nazeer Ahmed, *Editor*
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INTRODUCTION

The scope of *Hydraulics of Wells* was designed in a manner so as to familiarize the reader with the subject matter of hydraulics of wells as related to the production of groundwater for multipurpose usages. The potential topics, which were considered useful and pertinent to the water well industry for public and private consumers, were researched thoroughly and included in the text material. The following sections summarize the technical material presented in the manual through eight chapters and six appendices.

Chapter 1 provides basic information on groundwater as related to the hydrologic cycle, physical character of porous media, aquifer systems, ability of aquifer to store water, the Darcy equation (as applicable to flow in porous media), three-dimensional groundwater flow, anisotropy, groundwater flow equations, initial and boundary conditions, confined and semiconfined aquifers, and unconfined aquifers. Solved design examples demonstrate the fundamental concepts of flow in porous media.

Chapter 2, in general, outlines the determination process of total dynamic head consisting of different components of head loss, plus the static head as the groundwater flows from the outer limits of the cone of depression to the extraction well and the pumping equipment, which, in turn, moves the pumped groundwater to its final destination. The head loss components are studied thoroughly pertaining to the aquifer formation, damage zone, filter pack, well screen, wellbore, well casing, and suction and delivery pipes. The difference in the static water level and the pumping water level is designated as the total drawdown in the well. From a practical point of view, the design concept of total dynamic head is detailed for three different, real life situations: the groundwater discharge into the free atmosphere, service main, and overhead tank. To develop the total dynamic head in a pumping-plant configuration, the application of two independent, physical means of power supply—the electric motor and the internal combustion engine—is presented. This chapter, however, also describes three different types of pumping plant efficiency terms based on the concept of head loss, static head, well discharge, and power supply requirements as well efficiency at the level of total drawdown, wire-to-water efficiency at the level of electric motor, and the overall efficiency at the level of internal combustion engine. Solved design examples are provided to illustrate the application of the head losses, total drawdown, total dynamic head, and different efficiency terms.

Chapter 3 is devoted to the design considerations of water wells and pumping equipment on the basis of a number of criteria derived from different disciplines, such as flow in porous media, hydraulics, and economics. Design of boreholes, casing and screen pipes, filter packs, formation stabilizers, and the pumping units are described in detail. A number of flow equations and general information are provided to determine the dimensions of water wells and pumping equipment parameters. Because emphasis is placed on the economic considerations in the designing process, various cost-effective analyses are conducted, and actual test results are used for the determination of optimum well discharge and the selection of economical sizes of water wells and pumping equipment. Solved design examples are presented to explain various designing processes for water wells.

Chapter 4 deals with the well construction methods, installation of pumping equipment, well development, and testing for design of optimum discharge rate and pump settings. Specifically, it deals with the potential site assessment for a water well and commonly used drilling methods, such as the cable tool, direct circulation rotary drillings, and reverse circulation rotary drillings. The chapter describes a number of borehole logs as geophysical borehole logs, single-point resistivity logs, normal resistivity logs, guard resistivity (laterologs), spontaneous potential logs, acoustic/sonic logs, natural gamma logs, induction logs, and caliper logs. Isolated aquifer zone testing, water quality, and yield are described as well. The chapter also discusses destruction of old wells, placement of sealing materials, mechanical grading analyses, and lithologic description of formation materials. Installation of casing, screen, and filter pack; gravel feed pipes; sounding tubes; camera access tubes; centralizer installation; tremie pipes; compression sections; di-electric coupling sections; and interaquifer seals are portrayed in detail. Utilizing a number of techniques, principles of well development for artificially filter-packed and naturally developed wells are explained. Well and aquifer pumping tests are described utilizing the step-drawdown and constant-rate pumping techniques along with methods for analysis of pumping test data and collection of water quality samples. Finally, flowmeter and video surveys, plumbness and alignment surveys, and well disinfection are presented. For the benefit of the design professional, several field testing depictions of water wells are described. And, of course, a report summarizing the construction, development, and testing procedures of water wells then is required to be completed.

Chapter 5 describes the corrosion of pumping equipment and water well materials. It begins with a simple theory of corrosion by outlining the descriptions of electrode reactions, anode, cathode, passivity, and polarization. It presents a basic introduction of types of corrosion including electrochemical, microbial, galvanic, mechanical erosion, stray current, and crevice corrosions. Further, corrosive properties of water are explained in terms of dissolved ions, oxygen content, carbon dioxide, hydrogen sulphide, water discharge, pH, temperature, and scale deposits. Corrosion of well casings and screens is expanded by defining and describing different well zones with specific characteristics contributing to potential corrosion, such as external casing zone, atmospheric zone, splash zone, and submerged casing zone. In addition, the chapter provides detailed discussion of corrosion on pumping equipment, specifically by explaining the material selection, sand and gas contents, surface of pump impellers, cavitation, and general wear and tear on pumping equipment. To aid in the design of pumping equipment, prediction of corrosion rates are given in terms of scaling indexes, such as the Langelier Saturation Index and the Ryznar Stability Index. It is recommended that information on corrosion rate data be collected through laboratory, field, and service tests, as well as through electrochemical measurements, ASTM standards, and Internet resources. Evaluation of corrosion rate data can be computed in terms of weight loss and the length of time-exposure period. Corrosion protective measures include well screen placement and casing and well screen material selection. Protective measures are summarized, including materials, operation, protective coating, cathodic protection, and troubleshooting techniques for corrosion prevention. Finally, an example is presented based on field tests to determine the corrosion potential of various water well casing and screen materials. Analysis of corrosion rates and well life are analyzed for various materials.

Chapter 6 provides the fundamental definition of the theory of incrustation. It describes the chemical and bacterial analyses of groundwater responsible for causing the incrustation of pumping equipment and water well components, such as well screens. It describes the forms of incrustation and cites that water quality, dissolved solids, and the bacterial presence in water are main causes for the development and growth of incrustation. Also, it elaborates the effects of temperature, pressure, velocity changes, and thermodynamics of groundwater on the buildup of incrustation in the water-well systems. It enumerates forms of incrustation as chemical, physical, and biological. It elaborates chemical incrustation in the form of carbonate deposits, calcium sulfate, and metal oxides, such as iron oxide. Physical and biological incrustations and the character of iron oxide deposits are explained thoroughly. It emphasizes the field-testing of incrustation and critically reviews the timely maintenance of pumping equipment and components of water wells as a significant measure to arrest the further increase of incrustation. In addition, it narrates the methodologies of acid treatment, chlorine treatment, and polyphosphate treatment for incrustation and the extent of their benefits and advantages. Further, the concepts of chemical and bacterial incrustations are elaborated through two solved design examples.

Chapter 7 describes the wellhead protection concepts and EPA guidelines pertaining to the protection and quality control of groundwater for public consumption. It provides information about the fundamentals of groundwater flow, contaminant transport, wellhead delineation methods for the wellhead protection area including the arbitrary fixed radius, calculated fixed radius, standardized variable shapes, analytical methods, hydrogeologic mapping, and numerical flow and transport models. It provides a case study for a well site supported with numerical data for the protection of wellhead area comprising the wellhead delineation technique, hydrologic models, and vertical contaminant transport concepts. Further, it details a comparison between the wellhead protection area (WHPA) model and the analytical method. For this case study, after the field assessment is carried out, an actual contaminant inventory from the collected field data is compiled. This information then is used to implement and enforce the necessary precautions in the field to delineate the WHPA as mandated by U.S. EPA regulations to safeguard the groundwater resources. Solved design examples and other material presented illustrate the procedures for the determination of the wellhead protection areas.

Chapter 8 is devoted to the maintenance of operating water wells. It emphasizes the understanding of the usage of corrosion and incrustation preventive materials, design, and rehabilitation treatment choices to avoid well performance degradation and failure modes that may result during operation of water wells. In particular, it describes the prevention of corrosion, incrustation, and well fouling, as well as provides information for well cleaning chemicals, their handling, and safety features. Also discussed are preventive maintenance well treatment, well monitoring methods, records of well performance and well-component materials, troubleshooting guidance, and well maintenance schedules. It also details the importance of record keeping and computer software for preventive maintenance monitoring. It provides information about the economics of well maintenance, field and laboratory research on well maintenance, and emphasizes the importance of well maintenance through two solved design examples.

Several appendixes have been added as additional aids to the technical text material of the manual to advance the reader's understanding and to illuminate further the scientific and engineering field applications.

Appendix A offers an example of a complete water well system design that explains in detail the required information about well site investigations and sources of required data; geologic setting for drilling equipment; existence, quality, and availability of groundwater for its commercial exploitation; contamination potential, and remedial measures; compliance of groundwater laws and regulations; well construction, geologic logging, and aquifer zone testing; well design, filter pack design, and slot size selection procedure; pumping tests, optimal discharge, video survey, plumbness and alignment of wells; and rehabilitation, operation, and maintenance of water wells.

Appendix B provides detailed information about technical specifications for location, depth of well and other dimensions; hydrogeology, permits, certification, laws and ordinances; drilling methods and equipment; constructing and testing of water wells; geophysical borehole logs, yield, and water quality; design of casing, screen, and filter pack; casing and screen installation and alignment; development of the water well; well testing for yield and drawdown; step-drawdown test and constant rate pumping test; spinner and video surveys; well disinfection; well completion report; and bidding schedule.

Appendix C presents definitions and numerical data for the convenience of design computations, as well as testing, rehabilitation, maintenance, and operational procedures for water wells.

Appendix D includes a glossary with explanations of important terms used in the area of hydraulics of wells.

Appendix E lists SI unit prefixes, and Appendix F provides a conversion table for SI and U.S. customary unit systems, and numerical values of useful constants to help determine the solutions of practical design problems.