HYDROGEOLOGY OF PETROLEUM ENGINEERING

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Keywords: Crude oil reservoirs; Types of aquifers; Groundwater flow; Single-phase Darcy's law; Diffusion-advection equation; Petroleum product risks; Non-aqueous-phase-liquid (NAPL) classification; LNAPL contamination characteristics; DNAPL contamination characteristics; LNAPL entrapment in aquifers; Aquifer remediation aspects; Remediation technologies; Natural attenuation; Physical-chemical barriers; Hydraulic barriers; Multiphase flow formulas; Multiphase Darcy's law; Quantifying multiphase flow; Multiphase approximate methods; Pump-and-treat; One-well hydraulic barrier; One-well remediation system; Fractured permeable aquifers.

Contents

Summary

This chapter provides general perspective about major developments in hydrogeology that took place since the 80s of the last century. Some sections of this chapter refer to single fluid phase flow in porous media and contaminant transport in aquifers. The basic law of Darcy, the approximation of Dupuit for calculating flow in aquifers are discussed and evaluated. Major emphasis is given to characteristics of soil and aquifer contamination by liquid petroleum products called Non-Aqueous Phase Liquids (NAPLs).

Minute quantities of compounds present in such liquids, like BTEX (that are present in gasoline, kerosene and diesel oil) and chlorinated hydrocarbons, may cause great risks to human health and the environment. The characteristics of LNAPL (whose density is smaller than that of water) and DNAPL (whose density is larger than that of water) penetration into aquifers is represented. The different physicochemical and biological aspects of remediation are represented and evaluated. Some common technologies of soil and aquifer remediation are reviewed.

Effects of natural attenuation and their benefits are considered. Attention is given to different types of barriers containing areas of contaminant sources. Section 5 of the chapter concerns quantifying phenomena taking place in aquifers contaminated by NAPLs. The basic mass balances and constitutive equations in the domain are presented and evaluated. These equations require employing numerical models and carrying out calibrated simulations.

Currently, there are various public domain codes and those developed by private firms that can be used for such purposes. However, initial quantitative evaluation of basic characteristics of such operations is justified. Such an evaluation can be based on using a limited amount of data and simplified methods referring to a variety of alternative approaches. Some approximate methods referring to topics like: using hydraulic barriers, remediation of a homogeneous aquifer; and remediation of a permeable fractured aquifer are evaluated.

1. General Introduction

The objective of this chapter is to provide a survey of major concepts associated with petroleum hydrogeology. Within the list of references of this chapter the interested reader may find comprehensive amounts of information about a variety of issues associated with petroleum hydrogeology. However, as part of the encyclopedia of UNESCO devoted to Life Support Systems, this paper gives emphasis to the environmental issues of Petroleum Hydrogeology, namely penetration and contamination of soils and groundwater by liquid petroleum products.

Also about such issues, basic concepts and approaches are represented. In some cases, where conceptual approaches and calculations do not require profound professional knowledge, more details are given. Representation of some research work that is presently underway is also made in particular cases that concern fundamental issues of groundwater contamination and remediation.

Hydrogeology of petroleum engineering concerns phenomena associated with the presence of petroleum and liquid petroleum products in the subsurface. Deep permeable formations that include crude oil are the source of oil distillates and thereby also of energy for the human society. Spills of crude oil, oil distillates and liquid petroleum products, which are released into the environment, are of major concern for the environment, natural habitats and human health.

Liquid petroleum products released into the environment may produce significant risks of pollution to soils, geological formations and groundwater. Those issues are briefly covered in this manuscript. Geological formations that have the capacity to store and allow conveyance of crude oil are called "oil reservoirs". Such formations are usually located deep in the earth. Further, oil reservoirs often include top layers saturated with gases and often brines are also present in oil reservoirs.

Therefore, flow induced in the oil reservoir due to crude oil pumping is usually of several phases. The oil production industry found it necessary long ago to develop mathematical means for handling multiphase flow phenomena. As shown later, some of such means are presently applied to deal with environmental issues associated with the penetration of liquid petroleum products into the unsaturated (vadose) and saturated zones. Geological formations that have the capacity to store and allow conveyance of water are called "aquifers". Proper handling of events of liquid petroleum product penetration into aquifers requires knowledge and quantifying methods of multiphase flows that have been accumulated for many years by the oil producing companies.

Deep permeable formations that are oil reservoirs have been originated from the accumulation of the bodies of prehistoric sea animals and plants that became trapped in sediments. After millions of years, heat and pressure changed them into crude oil and natural gas. Crude oil and natural gas are usually found together in oil reservoirs. The oil reservoir is basically a trap of hydrocarbons, namely the organic compounds incorporated with the crude oil and the natural gas.

The oil reservoir has a distinctive shape, or configuration, which allows storing and prevents the escape of hydrocarbons that have migrated into it. Reservoir shapes are basically traps of hydrocarbons of the following types: 1) structural trap: a deformation in the rock layer that contains the hydrocarbons, e.g., fault trap (Figure 1) and anticlinal trap (Figure 2), 2) stratigraphic trap (Figure 3), which forms when other geological formations seal a reservoir rock or when the permeability changes within the reservoir rock itself, and 3) combination trap (Figures 4 and 5), which occurs when more than one kind of trap forms.

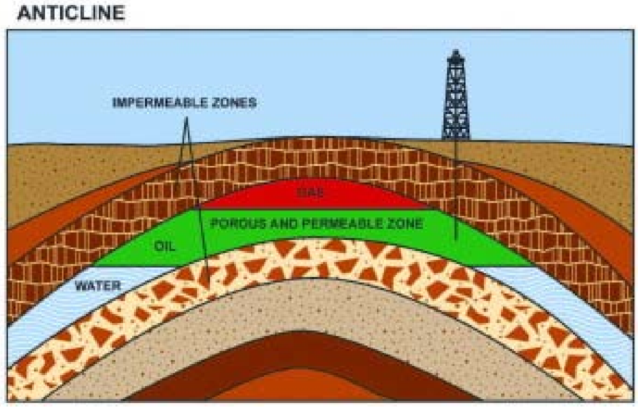

Figure 1. Anticlinal trap of oil
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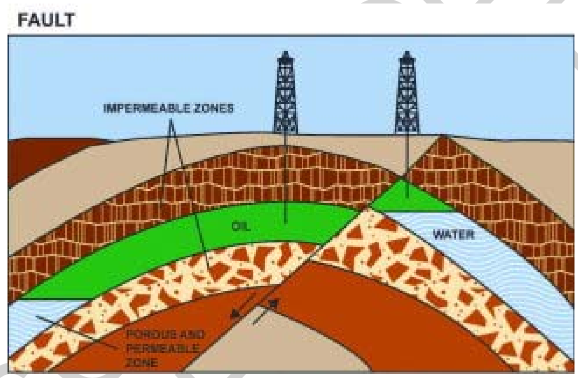

Figure 2. Fault trap of oil
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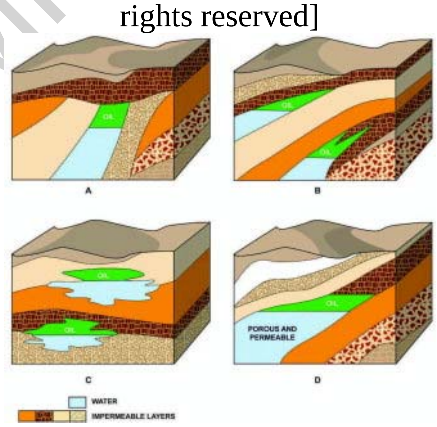

Figure 3. Examples of stratigraphic traps of oil

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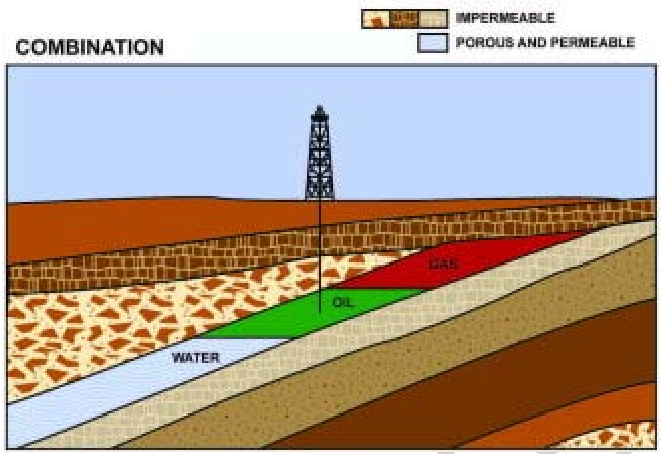

Figure 4. Combination trap of faulted anticline
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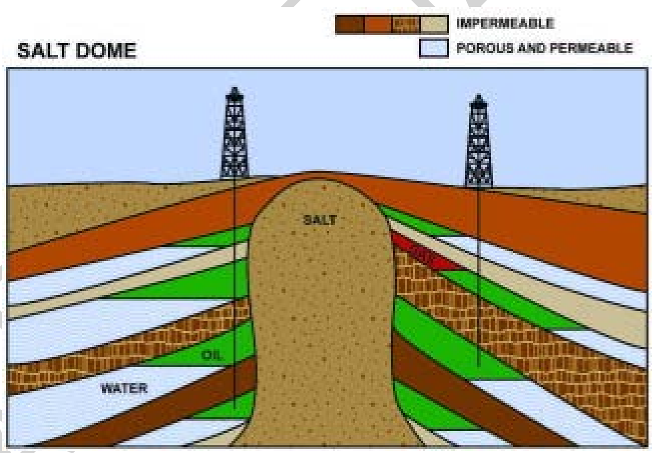

Figure 5. Piercement salt dome
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As stated before, aquifers consist of permeable formations that may store water. In general we identify two major types of aquifers: 1) Free surface (phreatic) aquifers (Figure 6), and 2) Confined aquifers (Figure 7). A free surface aquifer is characterized by an impermeable bottom, and water is accumulated on top of this bottom up to a level called "water table". The elevation of the water table is usually subject to seasonal and annual changes due to natural effects (precipitation) and manmade effects (pumping and/or injection).

The free surface aquifer is subject to natural recharge (accretion) by rain water or snow melt percolating through the unsaturated (vadose) zone that is located on top of the aquifer. A confined aquifer is characterized by impermeable bottom and impermeable top. The natural recharge of a confined aquifer is carried out via the vadoze zone of an area where the aquifer top is permeable, namely the confined aquifer starts as a free surface aquifer. There are various combinations of aquifers in different sites. Very often underneath the impermeable bottom of the phreatic aquifer there are permeable formations saturated with water, which comprise a confined aquifer. Such a system is typical of the coastal zone of Israel, as shown in Figure 8.

In this figure, the phreatic aquifer is called "The Coastal Plain Aquifer" and the confined aquifer is called "The Mountain Aquifer", as its recharge comes from the mountain area that is quite far from the sea shore. In various places, layers of impermeable formations are interbedded by permeable formations comprising a vertical series of confined aquifers. Very often the impermeable formations allow some contacts between the different vertical aquifers. Then the aquifers are called "leaky aquifers". The water saturating the aquifer is called "groundwater".

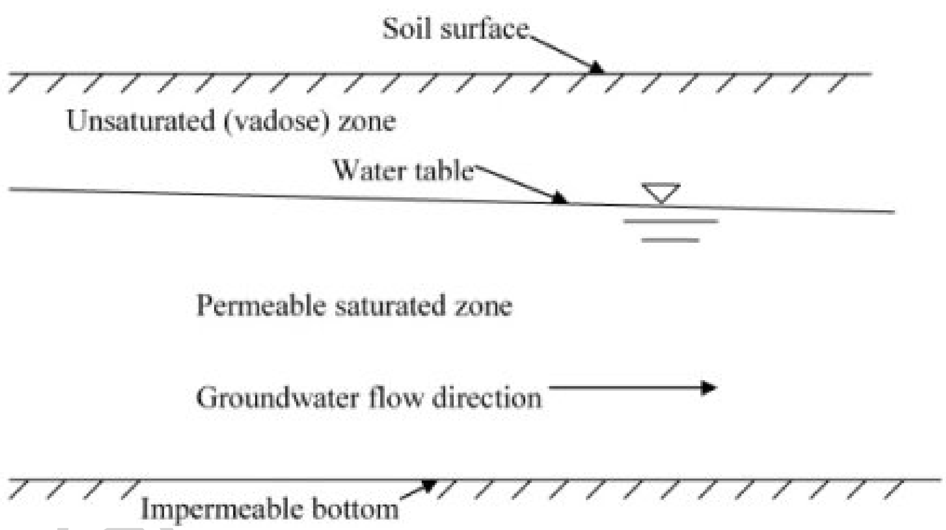

Figure 6. Schematic description of a free surface (phreatic) aquifer

The presence of groundwater in aquifers is associated with the global water cycle that starts with surface water, like oceans, seas and lakes that evaporates into the atmosphere and later returns to the soil surface as precipitations.

Part of the precipitations evaporates, another part leads to surface runoff, and another part infiltrates vertically through the vadose zone into aquifers. In the aquifers the flow is mainly in the horizontal direction towards rivers, lakes, seas and oceans.

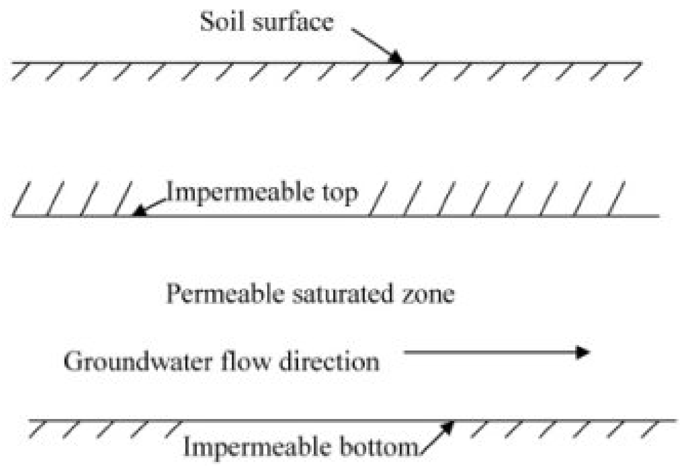

Figure 7. Schematic description of a confined aquifer

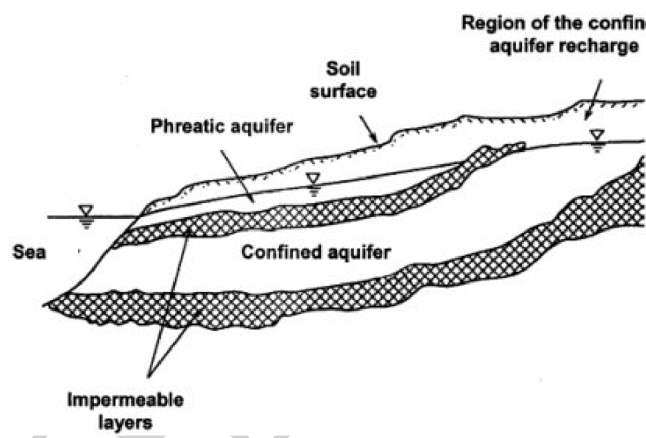

Figure 8. Schematic description of the two aquifer system in the coastal zone of Israel

Groundwater represents the major source of drinking water in most parts of the world. In arid and semi-arid areas, for many years the availability of sufficient quantities of water for the people and agricultural needs has represented a major national target. Well known are big projects of dams, which have created water reservoirs, and projects of transferring water from regions with rich water resources to regions with insufficient water resources. Such a project presently conveys water from northern parts of California to southern California. In Israel, the National Water Carrier delivers water from the northern part of the country to its southern part, which is a desert called "Negev".

During the last few decades of the 20^{th} century scientists of different disciplines connected with hydrogeology directed the authorities and the public opinion to be aware about the continuous deterioration of groundwater quality in most countries over the globe. It should be noted that the presence of minute quantities of some liquid petroleum products in groundwater may comprise a major threat to the environment, people and natural habitats, but there are some other pollution sources, whose effect is far from being negligible, e.g. the increasing chloride concentrations in groundwater that originate from irrigation and enhanced by using uncontrolled treated wastewater for such purposes. Also nitrate concentrations are subject to continuing increase mainly due to fertilization. However, this paper only concerns the hydrogeological aspects of liquid petroleum products.

For many years Petroleum Geology has been concentrated in identifying and exploring oil reservoirs. Different branches of Petroleum Engineering have been concentrated in efficient extraction of the crude oil and gases from oil reservoirs. Only during the last several decades of the 20th century Petroleum Hydrogeology started as a combination of hydrology, geology and petroleum engineering that gives attention to environmental issues associated with events of releasing into the environment liquid petroleum products, namely, hydrocarbons.

First steps in this direction were aiming at collecting or pumping oil distillates accumulated on top of the water table, mainly in refineries. Various private companies have acquired experience with such operations (e.g., the website http://www.freepatentsonline.com/5013218.html). Collecting these distillates has been originated from economic calculations. Later interest was growing about the risks to the environment and human health due to contamination of the unsaturated (vadose) and saturated zones by even minute quantities of different types of hydrocarbons.

The human society uses many oil distillates. Fuel supplied to our car engines is a major oil product. Thousands of gasoline stations are equipped with storage tanks; many of them have leaked hydrocarbons that contaminated the unsaturated and the water saturated zones. Many accidental events of oil spills from pipeline and regional and industrial fuel storage tanks have been reported. Therefore, as stated above, nowadays Hydrogeology of Petroleum Engineering incorporates significant reference to many issues associated with releasing hydrocarbons into the environment.

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Bibliography

Bear, J. (1972). *Dynamics of Fluids in Porous Media*, New York: American Elsevier. [This book presents a comprehensive review of most studies related to flow and transport in porous media prior to its publication]

Cohen, R.M., Mercer, J.W., Greenwald, R.M., and Beljin, M.S. (1997). *Design Guidelines for Conventional Pump-and-Treat Systems.* EPA/540/S-97/504. Washington DC: U.S. Environmental Protection Agency. [This reports provides qualitative information and quantitative details related to employing pump-and-treat systems]

Fetter, C.W. (1980). *Applied Hydrology*. Columbus, Ohio: Charles E. Merrill [This book provides basic concepts of geohydrology and single phase flow in aquifers]

McCarty, P.L., and Ellis, D.E. (2002). Natural attenuation. *Innovative Approaches to the On-Site Assessment and Remediation of Contaminated Sites* (eds. R. Danny, K. Demnerova), 141-181. Amsterdam: Kluwer. [This article provides a comprehensive review about the possible remediation of environments contaminated by DNAPLs]

Miller, C.T., Christakos, G., Imhoff, P.T., McBridge, J.F., Pedit, J.A. (1998). Multiphase flow and transport modeling in heterogeneous porous media: challenges and approaches. *Advances in Water Resources* **21(2)**, 77-120. [This article presents a review of basic mathematical material, numerical approaches and many studies, which concern multiphase flow in porous media]

NAVFAC (2002). *Surfactant-Enhanced Aquifer Remediation (SEAR) Design Manual*. NFESC Technical Report TR-2206-ENV. Washington DC: Naval Facilities Engineering Command. [This manual provides basic and technical details of SEAR]

Newell, C.J., Acree, S.D., Ross, R.R., Huling, S.G. (1995). *Ground Water Issues Light Nonaqueous Phase Liquids*. EPA/540/S-95/500, Ada, Oklahoma: EPA Robert S. Kerr Environmental Research Laboratory. [This report provides many details about groundwater contamination by LNAPL and possible avenues of remediation]

Noriris el al. (esd.) (1994). *Handbook of Bioremediation*, (eds. R.D. Norris et al.), Ann-Arbor: Lewis. [This book incorporates a collection of articles referring to bioremediation of soils and aquifers]

Polubarinova-Kochina, P.Y. (1962). *Theory of Ground Water Movement*, Princeton, New-Jersey: Princeton University Press. [This book presents a comprehensive description of using the potential flow theory for flow in porous media]

Rubin, H., Narkis, N., Carberry, J. (eds.) (1998). *Soil and Aquifer Pollution Non-Aqueous Phase Liquids Contamination and Reclamation*, Berlin: Springer. [This book incorporates a collection of articles referring to effects on the environment and human health of liquid petroleum products]

Rubin, H., Yaniv, S., Spiller, M., Köngeter, J., (2008). Parameters that control the cleanup of fractured permeable aquifers, *J. of Cont. Hydrol*. **96**, 128-149. [This manuscript provides details about approximate methods aiming at analyzing the remediation of aquifers made of fractured permeable formations]

Rubin, H., Shoemaker, C.A., and Köngeter, J. (2008). Screening of one-well hydraulic barrier design alternatives. *Ground Water* **46(5)** [This article incorporates complete details of the approximate method of screening alternative designs of hydraulic barrier]

Rubin, H., Shoemaker, C.A., and Köngeter, J. (2008) Implementing a method of screening hydraulic barrier design alternatives. *Ground Water* (under revision after review). [This article includes the manual and electronic spreadsheet with an example of screening hydraulic barrier alternative designs]

U.S. Environmental Protection Agency (EPA), 1996. Pump-and-treat ground-water remediation: a guide for decision makers and practitioners. EPA 625/R-95/005, Washington DC: EPA [This report provides practical information for implementing pump-and-treat remediation]

U.S. National Research Council (1994). *Alternatives for Ground Water Cleanup*. Washington DC: National Academy Press. [This report concerns issues and difficulties associated with achieving goals of soil and aquifer remediation]

Biographical Sketch

Hillel Rubin holds the Harry W. Labov & Charlotte Ullman-Labov Chair in Civil Engineering. He is a Professor at the Faculty of Civil and Environmental Engineering, Technion – Israel Institute of Technology, Haifa, Israel. He has obtained his B.Sc., M.Sc. and Ph.D. at Technion. His academic interests focus on Hydrology, Contaminant Hydrology; Remediation of Soils and Aquifers; Hydraulics; Hydraulic Structures; Collection Systems; Pipelines; Environmental Fluid Mechanics. He is the senior author and chief editor of 3 books in English, more than 100 articles in refereed journals, hundreds of articles in conference proceedings, many articles in professional Hebrew journals and hundreds of scientific research and professional reports. He has served several times as the head of the organizing committees of international workshops concerning soil and groundwater quality preservation and remediation. He has been a Visiting Professor for time periods longer than a year at the following universities: University of Florida; Princeton University; Kansas University; University of Michigan; University at Buffalo (SUNY); Cornell University (with the position of Mary S. Upson Visiting Professor); RWTH Aachen University, Germany.