GROUNDWATER IN ARID AND SEMIARID REGIONS

J.W. Lloyd
School of Earth Sciences, University of Birmingham, Edgbaston, Birmingham, UK

Keywords: arid zones, recharge, hydrogeological domains, groundwater resources potential, groundwater mining

Contents

Summary

Groundwater conditions in the semiarid and arid zones are described using a geological domain basis. The processes operative in recharge is discussed and the inferences for the low to zero recharge inputs outlined. The groundwater potential in the domains is considered and it is concluded that in many areas the future economic and social developments will depend upon carefully managed integrated water supplies based on a variety of sources, not exclusively groundwater. Some of the regional sedimentary basins are described as having extensive groundwater resources potential, although the development of such reserves will inevitably prove very expensive.

1. Introduction

There are many definitions of semiarid and arid climate, normally related to precipitation and temperature indices. Most are not reconcilable to groundwater conditions, which are probably best illustrated in terms of recharge, if indeed climate definitions are of any value, other than to provide a broad introduction to a region. An approximate indication of aridity in relation to groundwater is shown in Figure 1.

On Figure 2 a general depiction of worldwide aridity is shown.

In the following discussion the pertaining recharge conditions are defined. Hydrogeology is considered with respect to the dominating geological conditions, the groundwater resources occurrence, and the general management situations. Some comments are included about the difficult subject of future use and water resources sustainability.

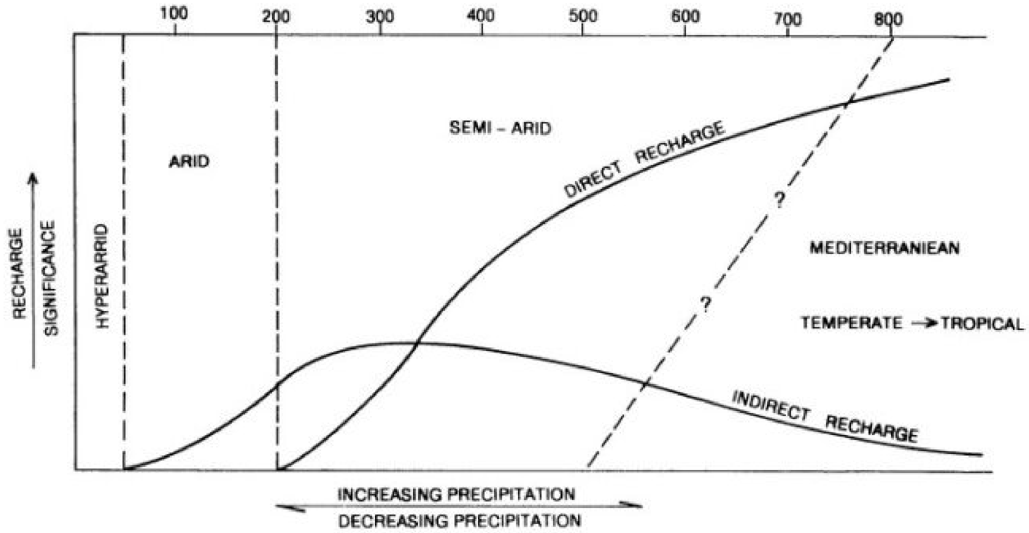

Figure 1. Definition of aridity using recharge criteria.

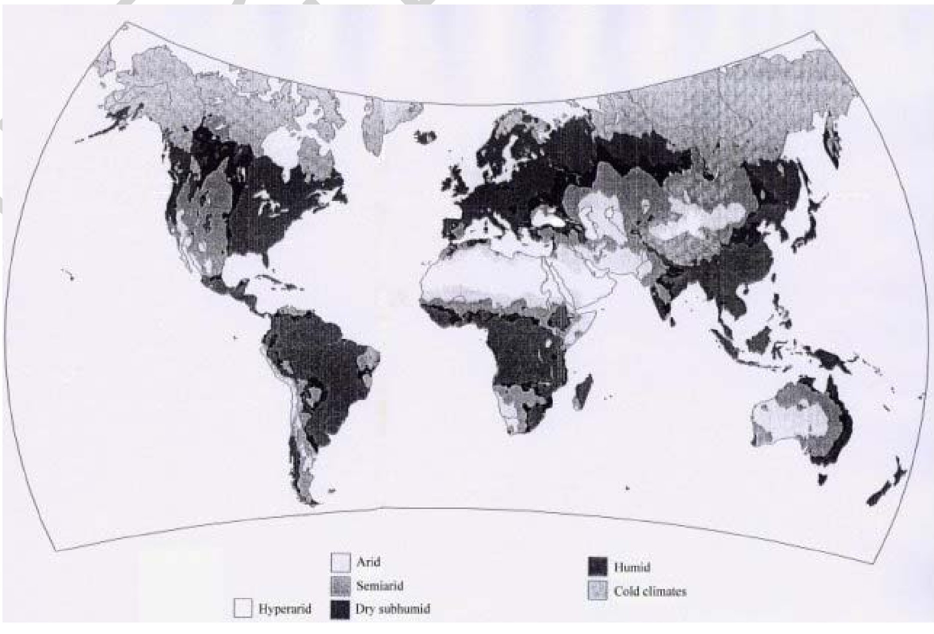

Figure 2. Global distribution of aridity.

2. Groundwater Recharge

In temperate and tropical regions considerable emphasis is placed on the assessment of recharge as it provides the basis for an understanding of groundwater resources sustainability. In most hydrological situations in such regions the dominant form of recharge is direct, in that infiltration entering the ground from precipitation, normally annually, eventually moves in a quasi-direct route to the free groundwater surface (water table), once any evaporative demands have been met. The recharge sustains base flow in the river systems and obviously, is an important factor in groundwater resources realisation.

Direct recharge is also a feature of semiarid regions, but as demonstrated in Figure 3, occurs on an intermittent basis owing to the variability in precipitation periodicity and volume, that is inherent in such regions. As illustrated in Figure 3, in some years direct recharge is substantial, but it can occur over very different time scales, while in some years no direct recharge occurs. The character of the recharge results in very variable base flow and much more associated water table lowering than in temperate, or tropical regions. Consequently, during periods of high volume flood runoff, influent river conditions are prevalent in semiarid regions and recharge can readily enter the ground indirectly from the runoff. Semiarid regions are therefore characterised through the significant occurrence of both direct and indirect recharge, in relative terms.

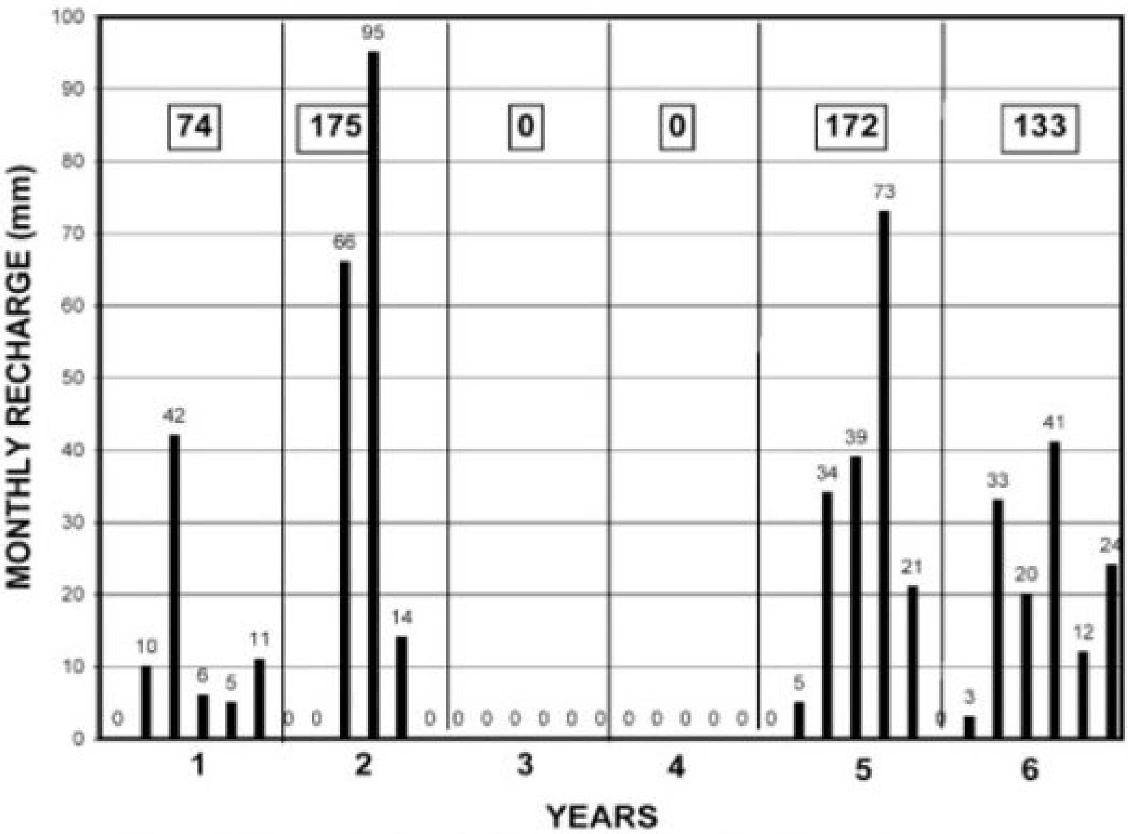

Figure 3. Example of semiarid region recharge from the eastern Mediterranean showing monthly occurrence for October to March with annual totals (mm).

Regional direct recharge assessments are usually carried out using soil moisture balance calculations (e.g. Lloyd *et al*., 1966; Caro and Eagleson, 1981; Simers *et al*.,1997) and calibrated through groundwater hydrograph simulation in transient numerical modeling. In some studies chloride balances have provided estimates of annual recharge input (e.g. Edmunds *et al*., (1992) in the Sudan), while in southern Australia and Africa some success in assessing long-term recharge has been obtained with stable isotope profile balances (Allison and Hughes, 1978; Edmunds and Gaye, 1994) and with nuclear fallout isotopes in USA (Phillips *et al*., 1988). An evaluation by Scanlon (1991) of chloride profiles in Texas sounds the warning that geomorphological features need to be taken into account when carrying out interpretations.

Indirect recharge is very difficult to assess. Lerner *et al*. (1990) provide various techniques, but unfortunately, measurement conditions frequently preclude the acquisition of reliable data so that only crude estimates result. Some discussion of the constraints of assessing indirect recharge is given below.

Arid regions receive much smaller recharge amounts than semiarid regions and in consequence, in groundwater terms, can be defined as being devoid of direct recharge, although in receipt of sparse intermittent indirect recharge. The most extreme form of aridity may be termed hyper-aridity, which describes those regions where no recharge in any form occurs that can be accounted in groundwater resources terms.

3. Hydrogeological Domains

For the purposes of this discussion the hydrogeological conditions appertaining in the most commonly occurring geological domains in semiarid and arid regions will be addressed as shown in Figure 4.

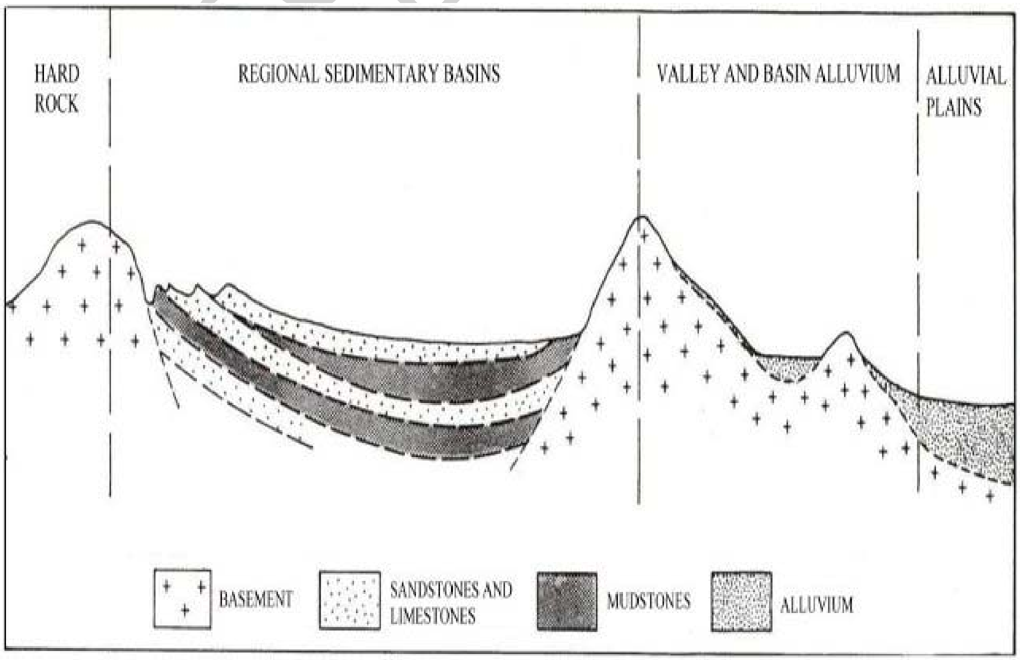

Figure 4. Hydrogeological domains.

3.1 Hard Rocks Domain

Hydrogeological conditions in hard rocks are extensively described by Wright and Burgess (1992) and Lloyd (1999). The rock types included in the domain are igneous intrusives and metamorphics. Lavas are excluded.

Irrespective of climate and usually lithology, these rocks typically posses extremely small primary porosity and hydraulic conductivity and consequently have little to offer in terms of groundwater resources. Secondary processes, however, can modify their groundwater potential with fracture and weathering leading to moderate increases in their aquifer characteristics. Unfortunately, as both of the secondary processes are non-uniform in extent the resultant aquifer characteristics are extremely variably distributed leading to complex and usually tenuous hydraulic continuity. As can be seen from Figure 5, assuming that fracture porosity is a major hydraulic factor the distribution must be variable in the extreme.

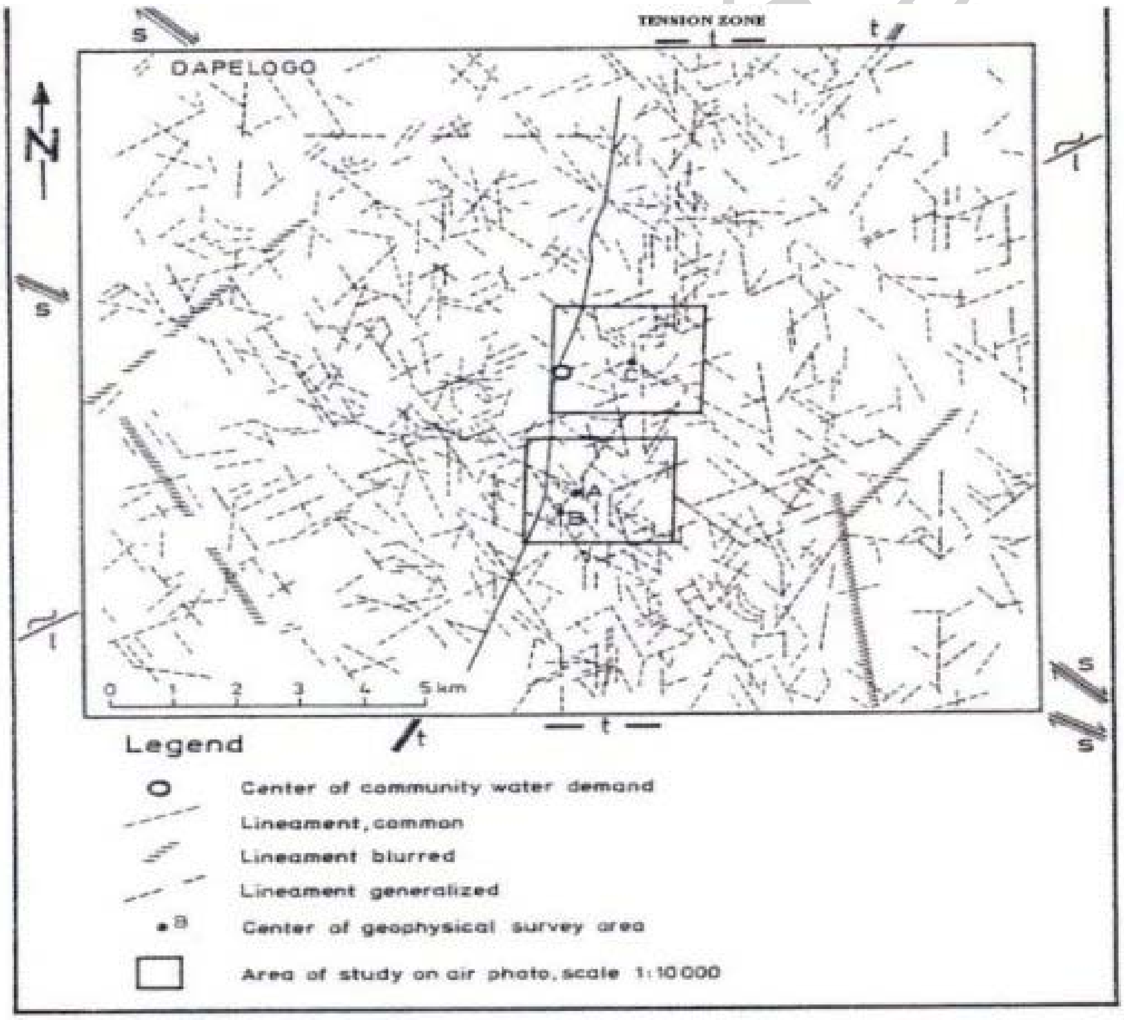

Figure 5. Example of fracture lineament mapping from Burkino Faso, using satellite imagery and air photos (after Boeckh, 1992).

Investigation techniques for fracture terrains in semiarid and arid terrains are highly developed (Sander, 1999). Structural mapping using satellite imagery and aerial photographs with ground truth, coupled with vegetation indexing, compiled into GIS format, provides an excellent basis for determining fracture distributions and structural style. With added well information statistics some progress is being made in understanding porosity extent, but inconsistency in fracture hydraulic characteristics make reliable hydrogeological assessment very difficult. The type of approach being adopted is summarized in Table 1.

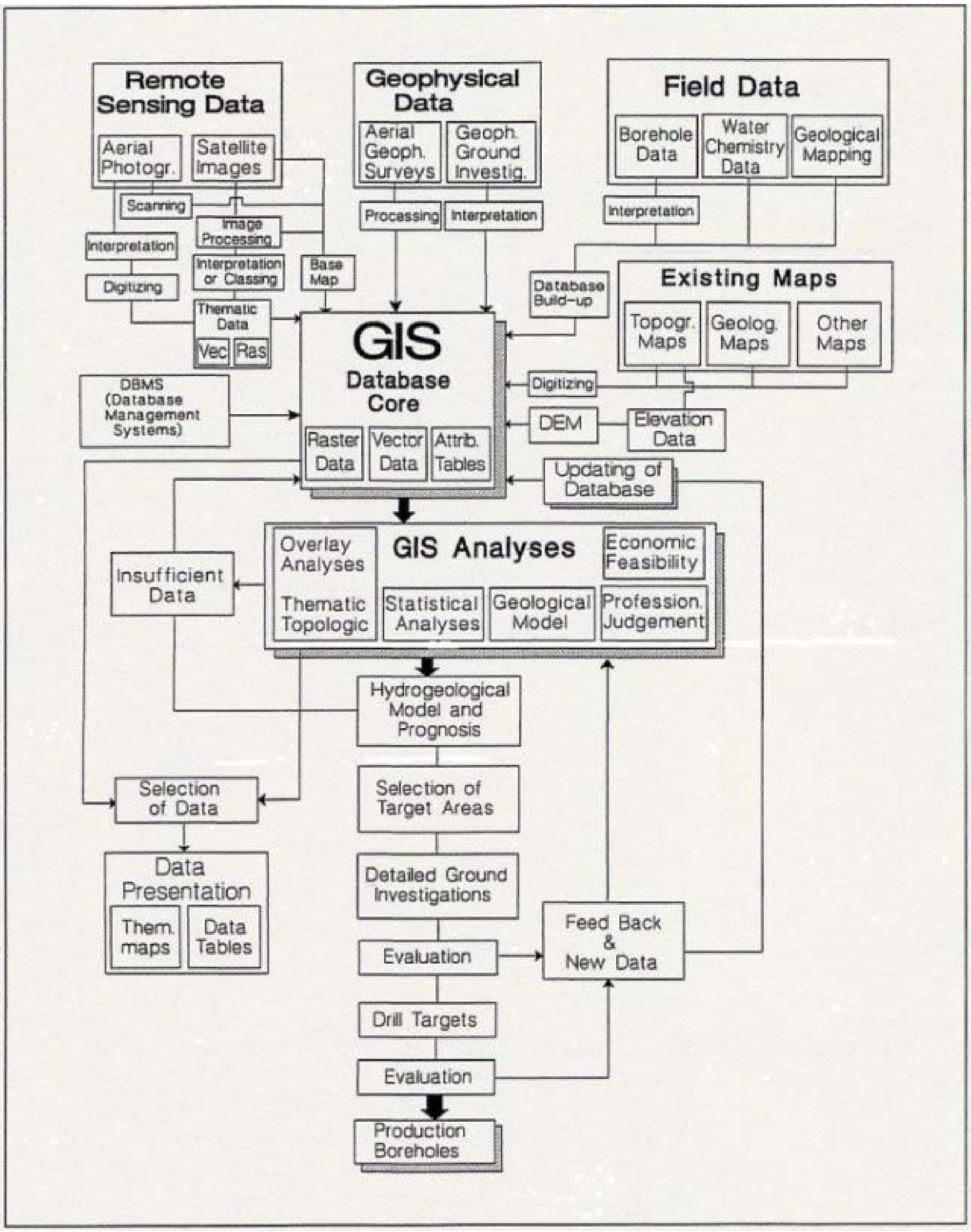

Table 1. Summary of GIS procedure used in evaluation of drilling targets in arid zone hard rock terrain (after Sander, 1999)

The character of fracturing can be modified by weathering, which is a feature of hard rocks in semiarid and arid areas and has been studied in detail in terms of mineralogical and lithological changes. Hydrogeological understanding is limited. While a universal feature, weathering is prone to preferentially effect fracture zones and therefore may enhance fracture porosity. An indication of the hydraulic properties in a weathered profile is shown in Figure 6. Unfortunately, the effects are very inconsistent and the resultant aquifer characteristics highly variable, as noted above. Irrespective, of the secondary process influences, hydraulic conductivity and porosity in hard rocks are very small compared to other aquifer rocks and would appear normally to decrease with depth. Generally, aquifer conditions in hard rocks tend to be unconfined.

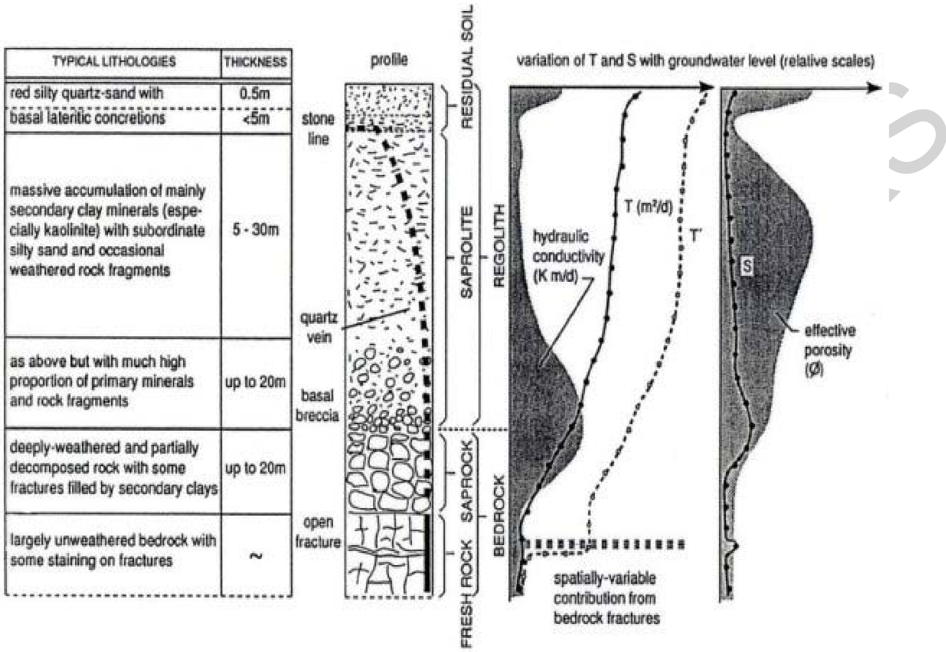

Figure 6. Example of hydraulic characteristics distribution in a weathered granite profile (after Chilton and Foster, 1995).

-
-
-

TO ACCESS ALL THE **25 PAGES** OF THIS CHAPTER,
Visit: http://www.eolss.net/Eolss-sampleAllChapter.aspx

Bibliography

Allison, G.B. and Hughes, M.W.1983. The use of natural tracers as indicators of soil-water movement in a temperate semiarid region. Jl. Hydrol. 60, 157-173. [Definitive study of stable isotope profiles in the soil zone]

Al Zubari, W.K. and Khater, A.R. 1995. Brackish groundwater resources in Bahrain: Current exploitation, numerical evaluation and prospect for utilization. Water resources management, 9, 277-297. [Paper with important inferences for groundwater resources in the arid areas]

Barker, M. 2001. World desalination market set to erupt. Water &Wastewater, 16,1,22-24. [Raising the message of desalination development as part of integrated resources]

Ben Zvi, A.1996.Quantitative prediction of runoff events in the Negev desert. In [Runoff, infiltration and subsurface flow of water in arid and semiarid regions. Eds. Issar, A.S. and Resnick, S.D.]

Water Science and technology Library, Khuwer Academic Publishers, Netherlands, 121-130. [Interesting paper on hydrological input in an arid area]

Boeckh, E. 1992. An exploration strategy for high-yield boreholes in the West African crystalline basement. In [The hydrogeology of crystalline basement aquifers in Africa. Eds. Wright, E.P. and Burgess, W.G.] Geol. Soc. London. Special Pub. 66, 87-100. [The paper is a good example of the developing approach to hard rock well location]

Caro, R. and Eagleson, P.S. 1981. Estimating aquifer recharge due to rainfall. Jl. Hydrol.53, 185-211. [Detailed explanation of recharge processes and assessment]

Chilton, P.J. and Foster, S.J.D. 1995. Hydrogeological characterisation and water supply potential of basement aquifers in tropical Africa. Quat. Jl. Engr. Geol. 24, 437-451. [A useful attempt to systematize the hard rock weathering zones for groundwater purposes]

Davis, S.N. and Turk, L.J. 1969. Best well depth in crystalline rocks. Ground Water, 2, 6-11.[A good case history of hard rock well yields in parts of USA]

Dillon, P. and Pavelic, P. 1996. Guidelines on the quality of stormwater and treated wastewater for injection into aquifers for storage and reuse. Australian Urban Water Research Assoc. Research Rept. 109, 54p. [Useful insight into the important aspects of water quality for aquifer storage and recovery]

Economic and Social Commission for Western Asia (ESCWA). 2001. The role of desalinated water in augmentation of the water supply in selected ESCWA member countries. E/ESCWA/ENR/2001/19, United Nations, New York, USA.72p. [Review of the situation in the eastern Mediterranean countries]

Edmunds, W.M., Darling, W.G., Kinniburgh, D.G., Kotoub, S. and Mahgoub,S.1992. Recharge study in the semi-arid Sudan. Jl. Hydrol. 131, 1-24.

Edmunds, W.M. and Gaye, C.B. 1994. Estimating the spatial variability of groundwater recharge in the Sahel using chloride. Jl. Hydrol. 156, 47-59. [Case history describing the use of chloride profiles to determine annual recharge]

El Baruni, S.S. 1995. Deterioration of quality of groundwater from Suani wellfield, Tripoli, Libya. Hydrog. Jl. 3, 2, 58-64. [Case history of saline groundwater encroachment on the Tripolitanian plain]

Entec. 1994. Artificial recharge of groundwater in northern Qatar. Report to the Min. Municipal Affairs and Agriculture, Qatar. 114p. [Description of field experiments to determine the potential for artificial recharge by well injection]

Greenman, D.W., Swarzenski, W.V. and Bennett, G.D. 1967. Groundwater hydrology of the Punjab, West Pakistan. U.S. Geol. Sur. Wat. Supply. Paper 1608-H. [Definitive hydrogeological study of the Indus valley]

Habermehl, M.A. 1983. Hydrogeology and hydrochemistry of the Great Artesian Basin, Australia. Aust. Wat. Res. Council Conf. Series 8, 3, 83-98. [Definitive description of the hydrogeology of the GAB]

Haist Kirkpartick. 1995. Qa Disi aquifer study, Jordan. Long term management of aquifer resources. Rept. to Ministry of Water & Irrigation, Government of Jordan, Amman. [Report providing the basis for the use of the Disi aquifer for the Amman water supply]

Hofmann, G. and Rambow, J. 1995. Spatial and temporal rainfall characteristics of the Wadi Al Jizi basin in northern Oman. Int. Conf. Water Resources Management in Arid Countries, Muscat, Oman. 2, 411-418. [Paper describing classical arid zone rainfall conditions]

Lamoreaux, P.E., Memon, B.A. and Idris, H. 1985. Groundwater development in the Kharga Oasis, Western Desert of Egypt. Environ. Geol. Water Sci. 7, 3, 129-149. [Case study describing oasis artesian well conditions]

La Touche, M.C.D. 1998. The water resources of Lima. Jl. Chart. Inst. Wat. Environ. Manag.11, 434-439. [Summary paper of water supply potential in the Lima basin]

Lerner, D.N., Issar, A. and Simmers, I. 1990. A guide to understanding and estimating natural recharge. Int. Assoc. Hydrog. Pub. 9. Hannover Heise. [Compendium of recharge assessment methodology]

Less, C.A.W. and Andersen, N.J.B. 1994. Hydrofracture – state of the art in South Africa. Applied Hydrogeology, 2, 2, 59-63. [Useful description of hydrofrac methods and results in hard rocks]

Lloyd, J.W., Drennen, D, and Bennell, B. 1966. A groundwater recharge study in north-eastern Jordan. Proc. Instn. Civil Engrs. 37. 701-721. [Semi-arid area recharge assessment case history]

Lloyd, J.W. 1969. The hydrogeology of the southern desert of Jordan. UNDP/FAO Pub. Tech. Rept. 1. Special Fund 212. 120p. [Description of the Disi Cambro-Ordovician aquifer]

Lloyd, J.W. 1986. A review of aridity and groundwater. Jl. Hydrological Processes, 1, 1, 63-78. [Summary paper examining arid zone groundwater controls and processes]

Lloyd, J.W. and Pim, R.H. 1990. The hydrogeology and groundwater resources development of the Cambro-Ordovician sandstone aquifer in Saudi Arabia and Jordan. Jl. Hydrol. 121, 1-20. [Review of the abstraction and aquifer responses]

Lloyd, J.W. 1994. The reality of recharge in semi-arid areas. Int. Conf. Water Resources Management in arid countries. Min. Water Resources, Muscat, Oman. Vol. 2. 466-479. [Paper outlining the inherent difficulties of recharge estimation]

Lloyd, J.W., Binsariti, A., Salem, O., El Sunni, A., Kwairi, A.S., Pizzi, G. and Moorwood, H. 1997. The groundwater assessment for the Western Jamahiriya System Wellfield, Libya. Proc. 30th Int. Geol. Congr. 22, 258-269. [Case history description of the Great Man-Made River western wellfield study]

Lloyd, J.W. 1999. Water resources of hard rock aquifers in arid and semiarid zones. Studies and reports in Hydrology, No. 58, UNESCO, Paris, 284p. [Guide to hydrogeological methodology in hard rocks]

Lloyd, J.W. 2002. Groundwaters in regional arid basins and their semiarid margins. Problematica de la gestion de las agues en regions semiaridas. Conf. Communidad de Valencia, Spain. 12p. [Review of the need for integrated supply systems based upon various sources]

McCuen, R.H. 1982. A guide to hydrological analysis using the US soil conservation methods. Prentice-Hall New York, USA. [Definitive guidelines]

Meldrum, J. 1995. Recharging water supplies in Oman. Int. Water Power & Dam Constr. June, 26-30. [Description of the Omani recharge dams]

Mukhopadhyay, A., Szekely, F. and Senay, Y. 1994. Artificial groundwater recharge experiments in carbonate and clastic aquifers of Kuwait. Water Resources Bull. Amer. Wat. Res. Assoc. 30, 6, 1091-1107. [Case history of artificial recharge experiments]

Phillips, F.M., Mattick, J.I. and Duval, T.A. 1988. Chlorine 36 and tritium from nuclear fallout as tracers for long-term liquid movement in desert soils. Water Resources Res. 24, 1877-1891. [Paper outlining the use of isotopes in soil profiles for recharge determinations]

Pike, J.G. 1970. Evaporation of groundwater from coastal playas (sabkha) in the Arabian Gulf. Jl. Hydrol. 11, 79-88. [Sabkha evaporative losses determined by using standard climatic parameters]

Pim, R.H. and Binsariti, A. 1994. The Libyan Great Man-Made River Project: Paper 2: The water resource. Proc. Instn. Civ. Engrs. 106, 123-145. [Case history description]

Pulido-Bosch, A., Pulido-Leboeuf, P., Sanches Martos, F., Gisbert, J. and Vallejos, A.2002. Coastal aquifers and desalinisation plants: a case study, Almeria, Spain. In [Water Resources Development and Management, Eds. Sherif, M.M., Singh, V.P.and Al Rashed, M.]

Balkema, Netherlands. II: 415-434. [Interesting report on the use of beach wells for desalination purposes]

Payne, R.D.G. 1995. Groundwater recharge and wells: A guide to Aquifer Storage Recovery. CRC Press Florida, USA. [Useful summary of the methodology of ASR]

Sander, P. 1999. Investigation techniques: mapping methods. In [Water resources of hard rock aquifers, Ed. Lloyd, J.W.] Studies and reports in hydrology, No. 58, UNESCO, Paris, 41-71. [Description of the use of satellite imagery and GIS in hard rock aquifers]

Scanlon, B.R. 1991. Evaluation of moisture flux from chloride data in desert soils. Jl.Hydrol. 128, 137-156. [Critique of methodology]

Simmers, I. 1997. Recharge of phreatic aquifers in (semi-) arid areas. Int. Assoc.Hydrog. Pub. No. 19, Balkema, Netherlands. 227p. [Useful summary of recharge assessment methods]

Thorweihe, U. and Heinl, M. 1996. Groundwater resources of the Nubian aquifer system. Technical University of Berlin, Germany. 95p. [Case history of the hydrogeology of the sandstone aquifer of the weastern desert of Egypt]

Ullman, W.J. 1985. Evaporation rate from a salt pan: estimates from chemical profiles in near-surface groundwaters. Jl. Hydrol. 79, 365-373. [Australian study of losses using soil profile data]

UNESCO. 1995. Les resources en eau des pays de l'OSS: evaluation, utilization et gestion. Int. Hydrological Prog. UNESCO, Paris. 80p. [Summary report of North African countries]

Viswanathan, M.N. and Al Senafy, M.N. 1998. Role of artificial recharge in the water resources management of Kuwait. In[Artificial Recharge of Groundwater. Eds. Peters *et al*.] Balkema, Rotterdam, Netherlands, 29-33. [Paper expounding the values of artificial recharge in arid conditions]

Watkins, M.D., Evans, D.A. and Lloyd, J.W. 1997. Continual Assessment of the Groundwater Resources of Lima. Jl. Chart. Inst. Wat. Environ. Man. 11, 440-445. [Paper describing the various studies carried out to determine the Lima groundwater resources]

Wheater, H.S., Butler, A.P., Stewart, E.J. and Hamilton, G.S. 1991a. A multivariate spatial-temporal model of rainfall in Southwest Saudi Arabia. I. Spatial rainfall characteristics and model formation. JL. Hydrol. 125, 175-199. [Description of the approach to understanding rainfall distributions and frequencies in arid zones]

Wheater, H.S., Onof, C., Butler, A.P. and Hamilton, G.S. 1999b. A multivariate spatial-temporal model of rainfall in Southwest Saudi Arabia. II. Regional analysis and long-term performance. JL. Hydrol. 125, 201-220. [Description of the interpretation of the information obtained in Paper 1991a for long-term applications]

Wright, E.P. and Burgess, W.G. 1992. The hydrogeology of crystalline basement aquifers in Africa. Geol. Soc. London, Soecial Pub. 66, 264p. [Book describing hard rock aquifer processes and giving case histories]

Biographical Sketch

John Lloyd is a Fellow of the British Royal Academy of Engineering and the Institution of Engineers. He holds a Doctorate of Science and a Doctorate of Philosophy, both in hydrogeology. He has worked for seven years in Jordan and three years in Chile, in the desert areas of those countries before being employed to lecture in the School of Earth Sciences of the University of Birmingham, UK, where he was appointed Professor of Hydrogeology in 1985. He has worked extensively in arid areas in the Arabian Peninsula, North Africa, Australia, South America and Southern Africa. His main interests are the study of groundwater flow systems and the methodologies of groundwater resources development under semi-arid and arid conditions.