Methods of Groundwater Recharge Estimation in Arid Regions

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Abstract

Groundwater recharge estimation has become a priority issue both in humid and arid regions for water management and conservation, especially in arid regions like Arabian Peninsula. Numerous methods are being used for recharge estimation, including the water-balance, Darcy's law, soil physics, chloride mass-balance and environmental isotopes technique. One method might be applicable in a certain environment, but proves inappropriate in others. The geologic complexities, lack of information, low rainfall, and the numerous mechanisms interacting to move water through the system pose a challenge to appropriate estimation of recharge. This paper discusses the various methods for recharge rate estimation applied in arid environments, their extent of applicability, with comparisons and contrast.

Keywords: Rainfall, Recharge Estimation, Arid Regions, Arabian Peninsula

Introduction

Water is the main key factor of life on the Earth. In arid and extremely arid regions, groundwater is a significant part of the total natural resources. Groundwater recharge, the flux of water across the water table is arguably the most difficult component of the hydrologic cycle to measure (Hogan et al., 2004). Recharge becomes the most significant element after the rainfall occurrence, but it direct calculation is not possible. Hence, the recharge rates in arid region are small and must be estimated with care and accuracy. Due to the variety of spatial and temporal scale-aquifer, recharge estimation may be required in time scale ranging from days (in shallow alluvial, fractured and karstic aquifers) to thousand of years (in deep and mine aquifers).

Groundwater recharge rates and mechanism in arid and extremely arid regions are subject of many techniques and methods all over the world. Different methods can be used to estimate groundwater recharge, such as empirical approaches, water-balance techniques, tracer techniques and others depending on data availability and the field situation (Eagelson 1979; Lerner et al.,1990; Flint et al., 2002; Edmunds et al., 2002; Scanlon, 2004) during the last two decades. Carter et al. (1994) summarize previous rain-fed groundwater recharge studies in semi-arid and arid regions around the world. The groundwater recharge percentages of these studies range from 1 to 30% of the local rainfall. Tracer techniques, such as environmental isotope and chloride mass-balance (CBM), have been commonly used in the overall domain of water resources development and management (Fritz and Fontes, 1980; Wood and Sanford 1995; Wood and Imes 1995; Wood 1999; Shi et al., 2000; Kattan 2001; Scanlon, 2004). In fact, the application of these relatively new techniques has played an important role in solving the envisaged hydrogeological problems that cannot be solved by conventional methods alone. (IAEA, 1980, 1983; Clark and Fritz, 1997).

With the exception of Arabian Shield and Oman Mountainous, the Arabian Peninsula, where there are no perennial rivers or surface water, is characterized by very little, unpredictable , and irregular occurrence of rainfall which may be very intense in local storms. Accordingly, the magnitude and distribution of rainfall vary from place to place and from time to time according to seasonality and topography. Describing and predicting the rainfall variability in space and/or in time are fundamental requirements for a wide variety of human activities and water projects.

Because of rapid economic growth and lack of rainfall in the Arabian Peninsula countries, the use of groundwater resources has increased dramatically. The human activities can be sustained based on a good management of groundwater storage volumes without significant problems. However, recharge rate estimation in arid regions involves a large degree of uncertainty due to low rainfall and high evaporation.

Recharge in the Arabian Peninsula, which has different topographic features, is often considered as the sum of several distinct processes occurring in different areas of the Peninsula. Arabian Shield, Oman Mountainous and their wadis are viewed as significant sources of recharge due to the orographic and monsoon rainfall effects from Atlantic and Indian oceans. The rest of Peninsula receives rainfall from cyclonic storms that penetrate the area from the Mediterranean sea (Nouh, 1987; Şen 1983; Subyani; 2004). Recharge can either occur through alluvial deposits of stream channels of Arabian Shield and Oman Mountainous (wadis) or through fractures in the crystalline bedrock. Combination of short and intense mountain storms, topography and limited infiltration capacity of soils results flash floods and surface runoff (Alehaideb, 1985; Rizk et. al, 1998). In the rest of the Peninsula, the basin floor receives significantly less amount of rainfall which occurs by convective and cyclonic storms, but makes the vast majority of the land surface. Recharge in these basins is a shallow effect and may be negligible in deep aquifers (Dençer et. al, 1974a; Caro and Eagleson, 1981; Lloyd, 1981; Subyani and Şen, 1991).

The purpose of this paper is to describe the hydrological features of the Arabian Peninsula and to delineate recharge zones. This study also describes the application of different methods for recharge rate estimation in arid environments, such as the Arabian Peninsula, their extent of applicability, comparison and contrast their of recharge estimates.

Geology of Arabian Peninsula

The Arabian Peninsula, lying in the southwest corner of Asia, is a huge crust of ancient sedimentary and volcanic rocks, deformed and metamorphosed and injected by plutonic intrusions. Except of Oman Mountains, the peninsula can be divided into two main structural provinces, the Arabian Shield and the Arabian Shelf. The Arabian Shield, which occupies about one-third of the peninsula, mainly consists of Neoproterozoic basement complex, with local Tertiary and Quaternary volcanics (Figure 1). The basement rocks suffered a prolonged history of deformation and metamorphism, and were intruded by igneous bodies of diverse ages and compositions. Tertiary and Quaternary basaltic flows and alluvial sediments cover part of the basement complex. (Powers et al., 1966; Brown et al., 1989; Alshanti, 1993).

The Arabian Shelf forms the remaining two-third of the peninsula. It lies to the east, north and south of the shield. Its foundation is a part of the same Precambrian plate that makes up the Shield. On this peneplaned basement lies a sequence of continental and shallow-water marine sedimentary rocks, ranging in age from Cambrian to Pliocene, dipping gentle away from the shield, and classified into a number of deep sedimentary basins. These sequences of beds dip gently and uniformly toward northeast, east and southeast away from the shield. Dips range from about one degree in older units to less than half degree in the Cretaceous and Eocene beds (Powers et. al, 1963; Alsayari and Zötl, 1978) (Figure 1).

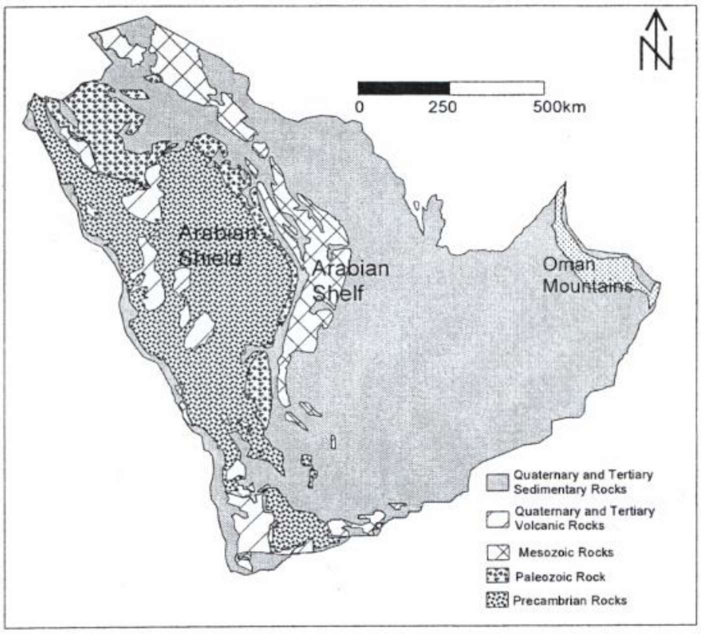

Figure 1. Geologic Framework of Arabian Peninsula.

Hydrology of Arabian Peninsula

In order to assess the groundwater recharge within the basins, it is necessary to define the predominant climate patterns that have an influence on rainfall distribution over these basins. The study of the water resources in the Arabian Peninsula is the identification of major factors affecting the magnitude and distribution of rainfall, such as altitude, various air mass movement, distance from moisture source, temperature, pressure, and topography.

The climate pattern over the western province can be best described by considering the various air masses that affect the rainfall distribution over the area considered. The influence of the various air masses and the rainfall pattern over the peninsula were discussed and mapped by several investigators (Şen, 1983; Alehaideb, 1985).

Air masses influencing the peninsula's climate are illustrated in Figure 2. It shows that there are three major fronts of moisture flowing into the peninsula. The monsoon front during the late fall and summer (maritime tropical air mass) that reaches the area from south, southwest, and southeast. This front originates from Indian Ocean and Arabian Sea and brings the warm and moist air. Outbreaks of westerly air become more frequent and are characterized by medium to high intensity of rainfall over the south and southwest of the peninsula. This front often picks up further moisture while moving through the Red Sea trough.

The continental tropical air masses, which are warm and moist, come from Atlantic Ocean through the middle and north African Continent. The maritime polar air masses are derived from the eastern Mediterranean Sea. During early winter the Mediterranean-born maritime air increasingly disturbs the monsoonal air movement and displaces it in the low altitudes. Generally, these maritime depressions draw the tropical continental air masses into warm sectors and extreme weather conditions occur, which are associated with the passage of very warm sector. Both the continental tropical and maritime polar air masses move toward the east and prevail in winter (Şen, 1983; Alehaideb, 1985, Subyani, 1997).

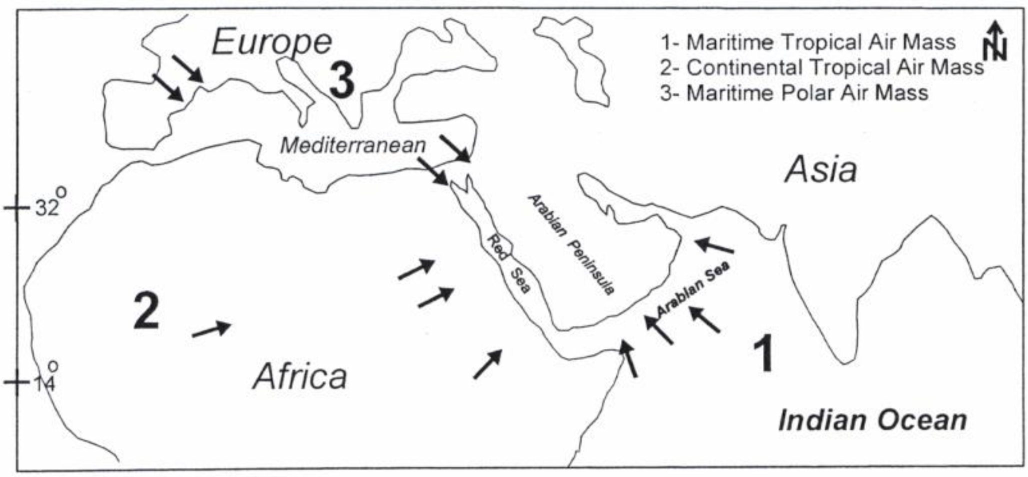

Figure 2. Air Masses Movement Over the Arabian Peninsula

Rainfall

Over the Arabian Peninsula, rainfall is very limited and varies from year to year, but it occurs every season in the mountains areas. The rainfall often occurs as thunderstorms of very high intensity during a local storm followed by dry periods. As mentioned earlier, autumn rainfall is related to local diurnal circulation, summer rainfalls to the monsoons, and winter and spring rainfalls to the African-Mediterranean interaction. Generally, rainfall in the study area is located under the influence of subtropical and orographic conditions.

The mean annual rainfall distribution map is presented in Figure 3, which shows the spatial variation of rainfall. This figure also reflects the topographic impact; hence annual rainfall generally increases with elevation in Yemen and Asir Mountains (ranges from 200 to 1000 mm/year). In addition to the winter orographic effect, monsoon season is very important factor which gives rise to heavy rainfall in the mountains area. The rest of the Arabian peninsula probably has an average annual rainfall of less than 200 mm. Indeed, parts of the vast interior, north and middle of the peninsula receive less than about 100 mm/year. Desert areas have had no rain for periods of several years.

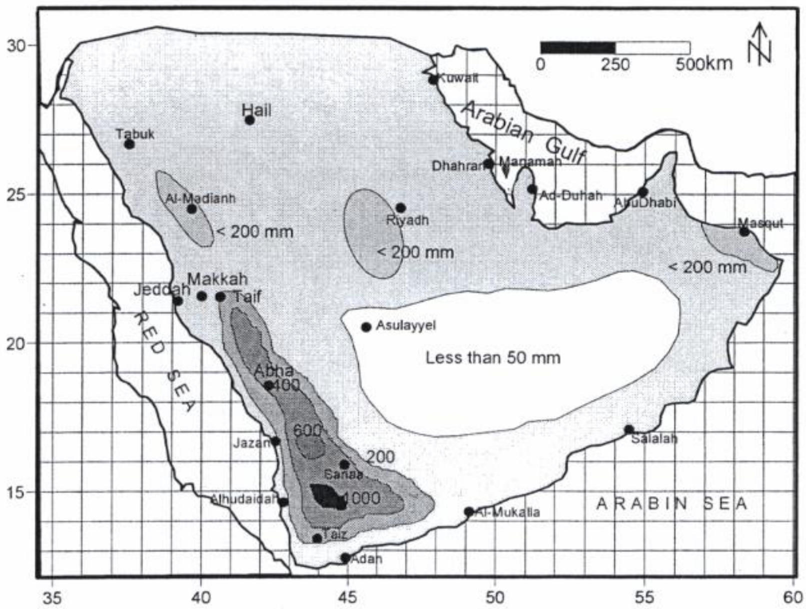

Figure 3. Generalized annual rainfall of Arabian Peninsula.

Recharge Methods Estimation

Groundwater recharge, the flux of water across the water table is arguably the most difficult component of the hydrologic cycle to measure (Hogan et. al, 2004). Recharge becomes the most significant element after the rainfall occurrence, especially in arid regions. Many researchers have applied different approaches to estimate groundwater recharge rates such as empirical approaches, water-balance techniques, tracer techniques and others depending on data availability and the field situation.

Recharge in Deep Aquifers

In central Arabia, where the annual rainfall is around 100 mm, there have been studies estimating the recharge contribution to some deep aquifers such as Minjur, Wasia and Biyadh. Sogreah (1968) estimated very roughly the recharge from the available hydro-climatological data, and they found the recharge rate is about 3-5 mm/year. On the other hand, Dencer et al. (1974b) propose two distinctive methods in calculating the recharge amount that goes through sand dunes around Khurais area (100 km east of Riyadh). First method depends on temperature, physical properties of the sand and shows that infiltration from rainfall in the sand dunes is a complex phenomenon. Other method is based on thermonuclear tritium content of the sand moisture. The authors concluded that the infiltration is about 20 mm/year, the threshold for this seems to be 50 mm of mean annual rainfall for the recharge to occur.

Furthermore, Sir MacDonald and Partners (1975) estimated the recharge amount through Wasia and Biyadh formations based on piezometry as well as transmissivity which vary areally and accordingly calculated the average recharge value as 5.2 mm/year. B.R.G.M. (1976) estimated the recharge from the available hydro-climatological data, which were reprocessed for the purpose of numerical model simulations leading to the recharge amount of about 6.5 mm/year. However, Caro and Eagleson (1981) estimated median annual recharge by using a dynamic model of annual water balance with the maximum depth of about 6 mm/year. They conclude that the results quantify the large uncertainty of annual recharge and the importance of considering a variable season length in such arid climate in central Arabia, and also these deep aquifers are being mined.

Subyani and Şen (1991) developed recharge outcrop relation (ROR) for calculation the amount of water that percolates into Wasia and Biyadh aquifers in central Saudi Arabia. The necessary hydroclimatological data are processed with the effective outcrop areas of the formations using Theisson polygon method. The results show that the amount of recharge is about 4 mm/year. Furthermore, investigations by kriging method of velocity distribution within the area, the regional groundwater velocity is obtained as 2-3 m/year which compares well with age dating of deep groundwater as show in Figure 4 (a and b). This means that a water drop takes about 35,000 years to reach the pumping area of Wasia and Biyadh aquifers.

Lloyd (1981) use an environmental isotopes in east of Jordan for confined and unconfined portions of sandstone and limestone aquifers to provide information for recharge mechanisms. He concluded that due to low rainfall and aridity, recharge from rainfall is rare. He also concluded that from ^{14}C data, most of the outcrop waters are modern, but t old waters are present in deep aquifers (6000-20,000 years).

In conclusion, deep aquifers in Arabian Peninsula that has catchment areas far away from pumping areas such as Saq, Tabuk, Minjur, Wasia, Biyadh, and Umm Er Radhuma which being mined. In addition, previous values of recharge rates obtained by different researches are only effective in few meters in shallow unconfined aquifers.

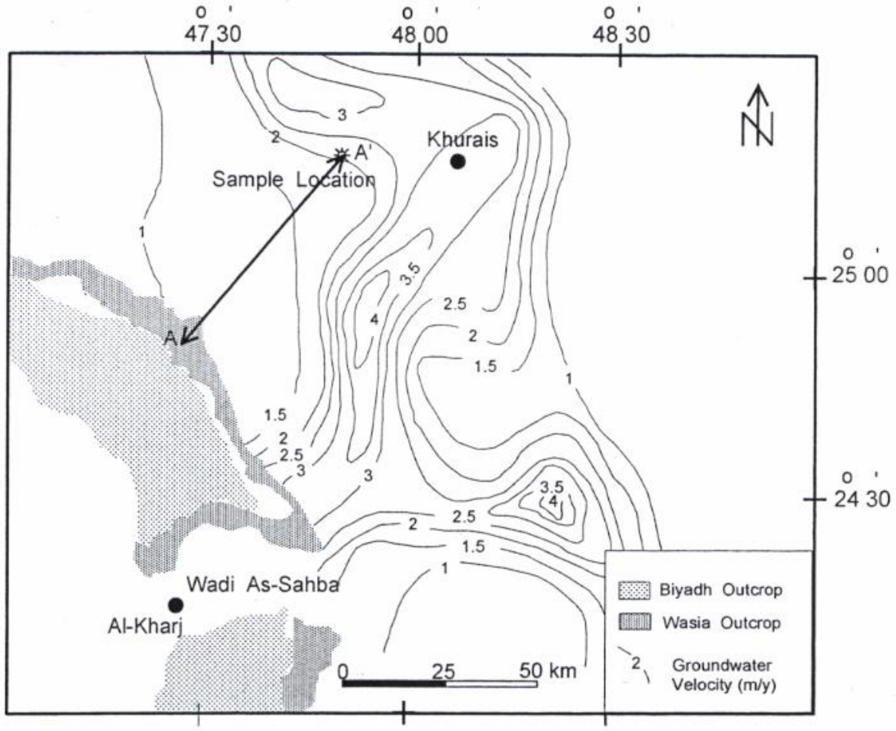

Figure 4 (a). Groundwater velocity map of Wasia Aquifer.

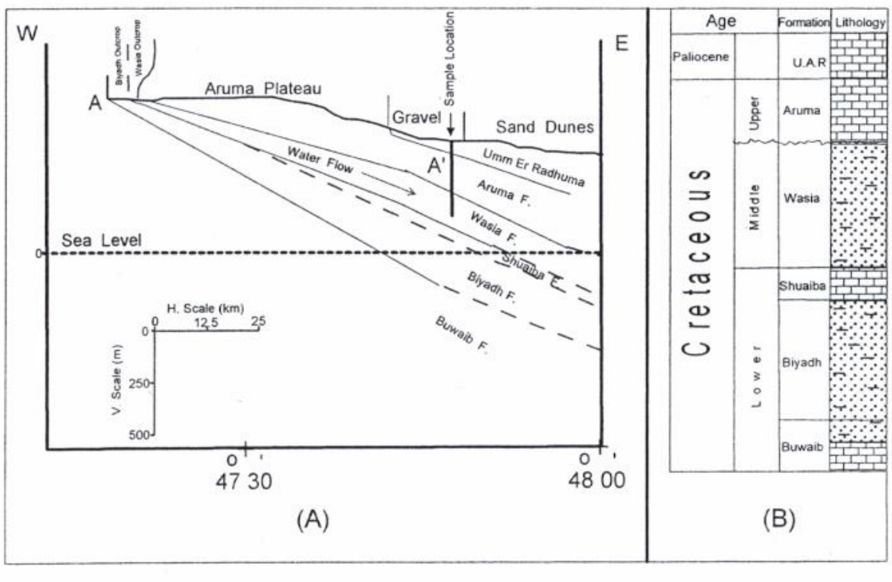

Figure 4(b). (a) Geologic cross-section and water flow, (b) Generalized stratigraphy.

Recharge in Shallow Aquifers

Based on lithologic and morphologic criteria, shallow aquifers can be divided into two main types. The first one is characterized by a certain continuity of characteristics in space, although this can obviously vary with the heterogeneity of the aquifer material and thickness changes of the formation(s) like wadi alluvium, surface and coastal deposits and basalt flows. The second type such as crystalline, igneous and metamorphic rocks, which are characterized by little or no original permeability but with secondary permeability acquired through fissuring and fracturing. Groundwater resources from these aquifers, derived from recharge or renewable resources, consist of that part of the rainfall, which infiltrates downwards to supply the aquifers. This infiltration can occur directly, immediately following a period of rainfall or at a later period from surface waters concentrated by runoff. These resources are dependent primarily on rainfall and secondarily on series of factors such a lithology, morphology of the drainage basin, fracturing or weathering, depth of the water table and vegetation.

Ghurm and Basmaci (1983) showed that recharge to rainfall ratio could be as high as 41% in the upstream reaches of the valleys. Also, Basmaci and Al-kabir (1988) noted that deuterium excess of groundwater samples collected from wadis proves recharge from high intensity summer rainfall. Down stream reaches of most of the catchments, which drain to the Red Sea in the west and to middle of the peninsula, are dry. The floods running over steep slopes disappear in alluvial fans. Environmental isotope studies over the coastal area of the Red Sea indicate groundwater ageing exceeding several thousand years (Bosch et al., 1980). Direct recharge of rainfall through fractures is a local phenomena and not significant. Some fracture systems, however, do transfer groundwater at large distances (Basmci and Hussein, 1988). Isotope analysis of some spring water in Saudi Arabia indicated mixtures of water recharged from different sources including present and paleowater (Bazuhair et al., 1990).

Abdul Razzak et al., (1989) applied the water balance approach to Wadi Tabalah in the southwestern region of Saudi Arabia. They estimated that 75% of rainfall was contributed towards groundwater recharge. Bazuhair and Wood (1996) successfully applied the CMB method for estimating groundwater recharge in some wadi aquifers of the western Saudi Arabia. They conclude that the recharge varied between 3 to 4% of rainfall.

Bazuhair et al., (2002) estimated the recharge rate of six alluvial aquifers of Arabian Shield using CMB method. These wadis are Al-Aqiq, Khulais, Wijj, Turabah, Abha and Jizan. Recharge rates to these aquifer systems ranges from 0.4 to 7% of average annual rainfall. They stated that the large variation in recharge rates is mainly due to rainfall variation and intensity, aquifer properties and climate conditions.

Subyani (2004) and Subyani and Şen (2005) modified CMB method by including some statistical approaches with effective recharge area and seasonal rainfall. They conclude that the recharge rates in most of the alluvial aquifers in arid regions range from 8 to 10% of effective rainfall.

In conclusion, Shallow aquifers such as wadi deposits, basalt flows and fractured crystalline rocks received a good amount of rainfall that can infiltrate directly to shallow groundwater storage. The rate of recharge depends on hydrological phenomena such as rainfall intensity, runoff, temperature and evaporation, and on physical properties of the aquifer such as porosity, permeability, fracture spacing, surface weathering and watershed properties. In general, recharge rate in arid regions does not exceed 10%.

Conclusion

Quantifying recharge rates in arid and extremely region such as Arabian Peninsula is difficult because of the large variability in topography, geomorphology, geologic complexities, and the numerous mechanisms interacting to move water through the system, lack of information and also spatial and temporal variability in climate and rainfall distributions. Many techniques have been applied in all over the World to evaluate recharge based on physical, chemical, isotopic and numerical modeling approaches. In the Arabian Peninsula, there is not sufficient information to apply such techniques. The following steps should be taken into consideration for recharge estimation.

1- Define the effective recharge area using isotopes techniques (e.g. $\delta^{18}O$, δD),
2- Define the effective monthly or seasonal rainfall. In other word, in the Arabian Peninsula, we have only spring and monsoonal rainfall that can be used for recharge calculation,
3- Chloride Mass-Balance method or water table monitoring measurements can be applied after rainfall event that is not less than 50 mm of monthly rainfall,
4- Due to uncertainties associated with each technique, it is best to apply as many different techniques as possible to better delineate recharge areas, processes and rates.

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طرق حسابات التغذيه للمياه الجوفيه في المناطق الجافه

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ملخص البحث

تعتبر حسابات التغذيه من الأمور المهمه جداً في ادارة موارد المياه والمحافظه عليها، وخاصة في المناطق الجافه مثل الجزيرة العربيه. ويمكن القول أن هذه الحسابات من الأمور الصعبه والساخنه في مناقشات حسابات التغذيه. وهناك عدة طرق ونظريات تطبق لحساب التغذيه مثل طريقة الميزانيه المائيه، قانون دارسي، المحتوي المائي في التربه، ميزان الكلور والنظائر البيئيه. ولكل طريقه من هذه الطرق لها شروط وافتراضات ومدخلات قد تتناسب مع منطقه معينه ولا تتناسب مع أخري. وهذه الظروف مثل التركيب الجيولوجي وقلة وتباين توزيع الأمطار ووجود عوامل تأثر علي حركة المياه الي باطن الأرض وقلة توفر المعلومات تعتبر من التحديات لحساب التغذيه للمياه الجوفيه. وهذه الورقه تستعرض الطرق المختلفه لحسابات التغذيه في المناطق الجافه ومشاكل تطبيقها وتناقش الإختلافات في النتائج.