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International Groundwater Congress in India and Abroad

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Abstract

International groundwater congress (IGWC) established in the year 2002 to cater the needs of groundwater professionals at various levels. It is truly needed a platform, where professionals working in the field of groundwater and its allied areas may come together and discuss the various issues of our country in particular and at global level in general related with groundwater issues. It has now been expanded in an international arena to explore the possibility of providing the same platform at global level. In this regard, IGWC has organized International conferences annually at various places of India and it is 5th in series scheduled to be held at Aurangabad, Maharashtra, India during Dec.18-21, 2012. IGWC is now reorganized as Association of Global Groundwater Scientists (AGGS).

1. Scope

Natural resources viz. water, forest and other minerals is an integral part of the environment and its sufficient availability is very important to the efficient functioning of the biosphere. Water is also of vital importance to all socio-economic sectors-human and economic development simply is not possible without a safe, stable water supply. On the other hand, excessive water has also a destructive potential. Extreme events may have an impact not only on the human society but also on the aquatic and terrestrial environments. Water resources must be seen in the overall context of development.

The static forest and the dynamic water resources especially in quantity must be kept reserved. In many developing countries, groundwater plays a major life support to mankind, as it is the major source to support domestic needs and irrigation purposes. Groundwater occurs in a wide range of rock types and usually requires little or no treatment; therefore it is often the cheapest and simplest water supply option. However, the rising demand for water worldwide, mostly for irrigation, can lead to problems of over exploitation of these resources and conflicts with competing demands, especially with community potable supplies. In early days, abstraction from the shallow aquifer has been limited, mainly because water-lifting devices were animal-powered. However, since the 1950s groundwater abstraction in India and elsewhere has increased substantially, both as a consequence of the increase in the number of wells, and use of energized pumps capable of lifting water from deeper aquifer up to a depth of 200m and more with much higher yields. This rapid development of groundwater resources had resulted the declining of water table/levels rapidly in many parts of the Afro-Asian countries causing shallow wells to-dry up with a particular impact on those rural poor farmers unable to deepen their wells to chase the declining water levels. In coastal areas, declining water levels are also associated with the ingress of saline water, leading to reduced crop yields, loss of drinking water supplies and ultimately loss of both fertile land and water supply wells. These problems are very acute in those areas underlain by hard rocks, since the hard rock aquifers has limited storage capacity and stores only limited quantity. Further, in the semi-arid regions, the climatic conditions of low and variable rainfall limit recharge and make these aquifers susceptible to drought.

Long-term continuous decline of water level have resulted due to increased groundwater abstraction in many parts of India and elsewhere for the last many decades. This has resulted in deterioration of water quality and the widespread drying-up of wells in monsoon climatic regions due to 'failure' of the monsoon. Deepening of wells does not appear to be a viable option as most wells already fully penetrate the shallow weathered aquifer. This has resulted only debt trap of rural farming community.

Since more than 70% of population live in rural areas of developing countries and, given the importance of groundwater to the rural economy, it is clear that efficient management of groundwater resources is essential. Addressing the problem of over exploitation is a complex phenomenon. Traditional methods of groundwater management are a mix of regulatory (controlling the abstraction) and pricing the water and energy used for pumps. However, the above has never worked in any part of the over-populated developing countries. It is, thus imperative, to have an effective groundwater management policies to obviate the above hazards.

Groundwater pollution is another dimensional hazardous movement. The increasing demand for water to meet the needs of domestic, industrial and agriculture is placing greater emphasis on the development of groundwater resources. The over-exploitation of groundwater resources at many developing countries induces degradation of groundwater quality as well as the discharge of untreated industrial effluents are adding contaminants to groundwater system. Globally, pollutions are identified as microbiological pollution, organic pollution, salinisation, and total suspended solids. These are related to human (anthropogenic) activities such as agriculture, urbanization, industrialization, mining, land use change and climate change etc. The pollution of groundwater regime is not only due to sub-surface waste disposal, but is also attributable to the seepage of contaminants from the rivers and lakes, impoundment of toxic waste on unlined surfaces, indiscriminate spraying of insecticides, pesticides and excessive use of chemical fertilizers etc. The pollutant mass migrates with the groundwater flow and manifests itself even at places where one may least expect any contamination.

Some of the less hazardous contaminants include nitrates, sulphates, chlorides, suspended solids, mineral oil etc. However, if their quantities increase much beyond permissible limits, groundwater is rendered unusable. Still more toxic pollutants which are much more hazardous and have long term effects, are the toxic chemicals like arsenic, barium, boron, cadmium, chromium, cyanide and lead. There are several industries in the country, whose wastes containing such toxic chemicals have been causing serious groundwater pollution. Some of the biological pollutants include micro-organisms, which cause diseases like infective hepatitis, gastro-enteritis's, typhoid, dysentery etc. Radioactive nuclides such as 3H, 90Sr, 137CS, 226Ra etc., is yet another class of contaminants which enter the groundwater system from the nuclear waste disposal.

The contaminants gravitate and disperse in the unsaturated soil zone. Subsequently, they spread in the shallow saturated zone through advective (convective) migration and hydrodynamic dispersion. This process depends both on the groundwater flow velocities and the gradient of contaminant concentration. In deeper aquifers, where the groundwater velocities are relatively small, the rate of migration is slower and is governed primarily by the concentration gradient. This situation is prevalent in softer geological formations such as alluvial aquifers. In hard rock formations, the presence of fractures, fissures, joints etc., add another dimension to the transport of the pollutant mass. With the increasing use of groundwater for drinking purposes, it is imperative to study the movement of contaminants in an aquifer so as to predict their migration and work out suitable remedial measures. Based on a well-planned network for collection of geo-hydrological and hydro chemical data, a deterministic numerical model of mass transport in groundwater regime may be prepared which can help assess the rate and extent of pollutant migration. It can also provide guidelines for future planning of disposal operations and for controlling the existing contaminant plumes.

Therefore, it is important to anticipate and recognize such problems in time and to implement appropriate measures to control or mitigate them without delay. Many groundwater professionals in **India and neighboring SARC** countries believe that sharing knowledge and experience on groundwater matters on a worldwide scale is an effective strategy to identify and promote optimal approaches to the assessment, development and management of groundwater resources. This is what the Association of Global Groundwater Scientists (AGGS) alias International Groundwater Congress (**IGWC**), India intends to do by organizing seminars/symposia at various centers in the India and in the neighboring countries viz. Bangladesh, Srilanka, Pakistan, Nepal and Bhutan and publishing proceeding volumes and new findings among congress members. It is also emphasized to bring a scientific journal to publish the research findings of the groundwater scientists.

The idea on the formulation of this congress was crystallized by groundwater scientists and engineers who attended the last three International Groundwater Conferences (**IGC**) at Dindigul in Tamil Nadu during February 2002, JNU, New Delhi during 2006 and at TNAU, Coimbatore during February 2007, at Madurai during September 2011.

2. Objectives

Association of Global Groundwater Scientists (AGGS) alias International Groundwater Congress (IGWC) will contribute in the field of effective management of groundwater resources. It is a forum, where in the experts working on groundwater and other natural resources development and management will assemble and devise methods for the effective management for ensuring sustainable development and livelihood in the overstressed areas of the country and elsewhere.

AGGS is committed to work on the promotion of research for minimizing groundwater pollution and to advocate the effective use of groundwater for better health and sustainable livelihood through undertaking appropriate measures. It will also publish the scientific findings of the research carried out by the groundwater scientists both from India and abroad.

What the Forum can do?

The **AGGS** alias **IGWC** will contribute to provide information, training and research and will lead to an increased capacity of developing countries in the area of hydrogeology/hydraulics and water resources management. The new forum will lead to improved management and protection of groundwater resources through the collaborations of water resources professionals from universities, public water institutions, non-governmental organizations, public/ private sector professionals, international funding agencies and other relevant institutions. **AGGS** will mainly focus in organizing annual events at various centers in India and neighboring countries by bringing **AGGS** members and other International experts to discuss the latest development in the assessment and management of groundwater resources. It also plans to have some research activities in collaboration with National Institutes and International agencies on the understanding of hard rock aquifer system and development and management of coastal aquifer system.

Major Tasks and Activities

AGGS is envisaged as a functional network and collaboration of different organizations including Government Departments, IIT's, National Institutes/Laboratories, Universities, Water related Industries and NGOS for better sharing and collaboration on emerging issues in ground water management. SAGC will plan to bring experts in various fields to a common platform for exchange of new ideas, views and knowledge in a global platform that stimulates initiatives for the advancement of sustainable development and management of groundwater resources.

The Various Activities of IGWC are enlisted as follows:

- Organizing regular annual events for groundwater scientists from all over the globe to assemble and discussing the various new research developments elsewhere and how to solve groundwater quantity and quality problems pertaining to SAARC countries
- Organization of mass awareness meeting among school children and rural woman folk regarding the quality and scarcity of drinking water and how to create sustainable supply
- Impairing the scientific knowledge among school children, women and farmers about the identification of potential bore holes in hard rock and drought prone region
- Identification and development of innovative ideas for conservation of rainwater (rain water harvesting) and rain-fed forests
- Sustainable development of a watershed in a hard rock region
- Discussing problems and questions posed by farmers, the politicians, and technical cooperation agencies, general public and potential industrial clients
- Publishing the scientific findings of the research carried out by various groundwater scientists in peer reviewed journal i.e., Journal of Groundwater Research, IGWC.

Long-Term Goal

- Providing training to young groundwater scientists/engineers on Mathematical modeling to assess groundwater potential and pollution migration and thereby evolving optimal management schemes
- Collaborating with public sector water related institutions, municipalities, non-governmental organizations (NGO) and the private sector for the implementation of water management schemes
- Promoting projects that directly involve and benefit local communities.
- Initiating and sustaining the activities in the area of community-based research and the social, legal and economic aspects of groundwater resources management
- Promoting Joint research projects among scientists/engineers from India and its neighboring countries with leading research institution in the assessment and management of groundwater resources and pollution
- Development of new methodology to characterize the fracture aquifer geometry and understanding the flow dynamics of fracture system
- Development and management of coastal aquifer system
- Promoting the research development of viable and feasible technology for the treatment of contaminated aquifer system
- Publication of a periodic quality Groundwater journal in collaboration with likeminded International professional bodies viz. IAH, IAHS & ISGSD

Managing the Irrigation Water Requirements of Command Area of 4(L) Distributory of Pollachi Main Canal under Variable Rainfall Conditions

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Abstract

The 4 (L) distributory of Pollachi main canal, Parambikulam-Aliyar-Palar (PAP) basin has been selected for an in-depth water management study. The project area has been divided into two zones namely, A zone and B zone. Each zone would get water from the canal system once in every two years. From the analysis of rainfall data of the rain gauge stations located in Parambikulam-Aliyar-Palar basin, it was observed that there was a wide temporal and spatial variability in annual rainfall over the years. The lowest annual rainfall recorded was 210.6 mm (over the plain) in 2003 and the highest of 5346.4 mm (in the hills) in 2007. The average annual rainfall for the period 1988-2010 was 1372.1 mm. The irrigation water requirement for the crops grown in the 4 (L) distributory was estimated using AquaCrop3.1 model for the years 2000-2010. The total irrigation water requirement during deficit rainfall year (2002) was 58.4 percent which is higher compared to normal year (2008). During the excess rainfall year (2007), the demand was 5.32 percent lower than the normal year demand. Therefore, the conjunctive use management of surface and groundwater resources in a command area can play a significant role in managing water by distributing the water throughout the season, while also maintaining the long-term sustainability of groundwater resources.

1. Introduction

Rainfall variability widely influences the irrigation water requirement of crops grown in various command areas throughout India. Managing irrigation under scarcity using an integrated approach is a critical issue in irrigation planning. Understanding the vulnerability and resilience of irrigated command areas to climatic extremes viz., drought and excess water situation will be helpful to develop management strategies to mitigate unexpected adverse rainfall conditions. Fiedler (2003) derived station weights of rainfall using Thiessan Polygon and Isohyetal methods and found that more accurate spatial distribution was depicted by the Isohyetel method.

Parambikulam-Aliyar-Palar (PAP) basin is located in the south western part of the Peninsular India and covers the areas in Kerala and Tamil Nadu States. The PAP basin lies (except the Ayacut area) within the coordinates between 10° 10’ 00” to 10°57’20” N and 76°43’00” to 77° 12’30” E (Fig 1). The basin area lies within the Coimbatore district only and the Ayacut area is extended beyond Coimbatore and Triuppur districts up to Vellakoil, Erode district. In Tamil Nadu, there is a little scope for the augmentation of water supply to agriculture as the utilization of surface and groundwater resources have already crossed 95 percent and 78 percent of this capacity, respectively (Source: CWC, 2008 & CGWB, 2009). The net irrigated area in the state is around 25 lakh hectares in 1960 to 2010. But the share of irrigation by surface water resources (canals and tanks) reduced from 18.12 lakh ha to 12.19 lakh ha in 2010. But the share of groundwater irrigated areas increased from 6.45 lakh ha in 1960 to 14.18 lakh ha in 2010 (Seasons and Crop report, Tamil Nadu, 2010). The decline in canals and tanks was more or less compensated by the significant increase in the groundwater irrigated areas. There is an urgent need for improving the efficiency of existing irrigation projects, which will ensure its sustainability with the possibility of bringing in additional areas under its command. Estimation of spatial and temporal water availability from rain, surface sources and groundwater sources in the command area and assessment of irrigation water requirements for various crops are prerequisite for crop planning within the command area.

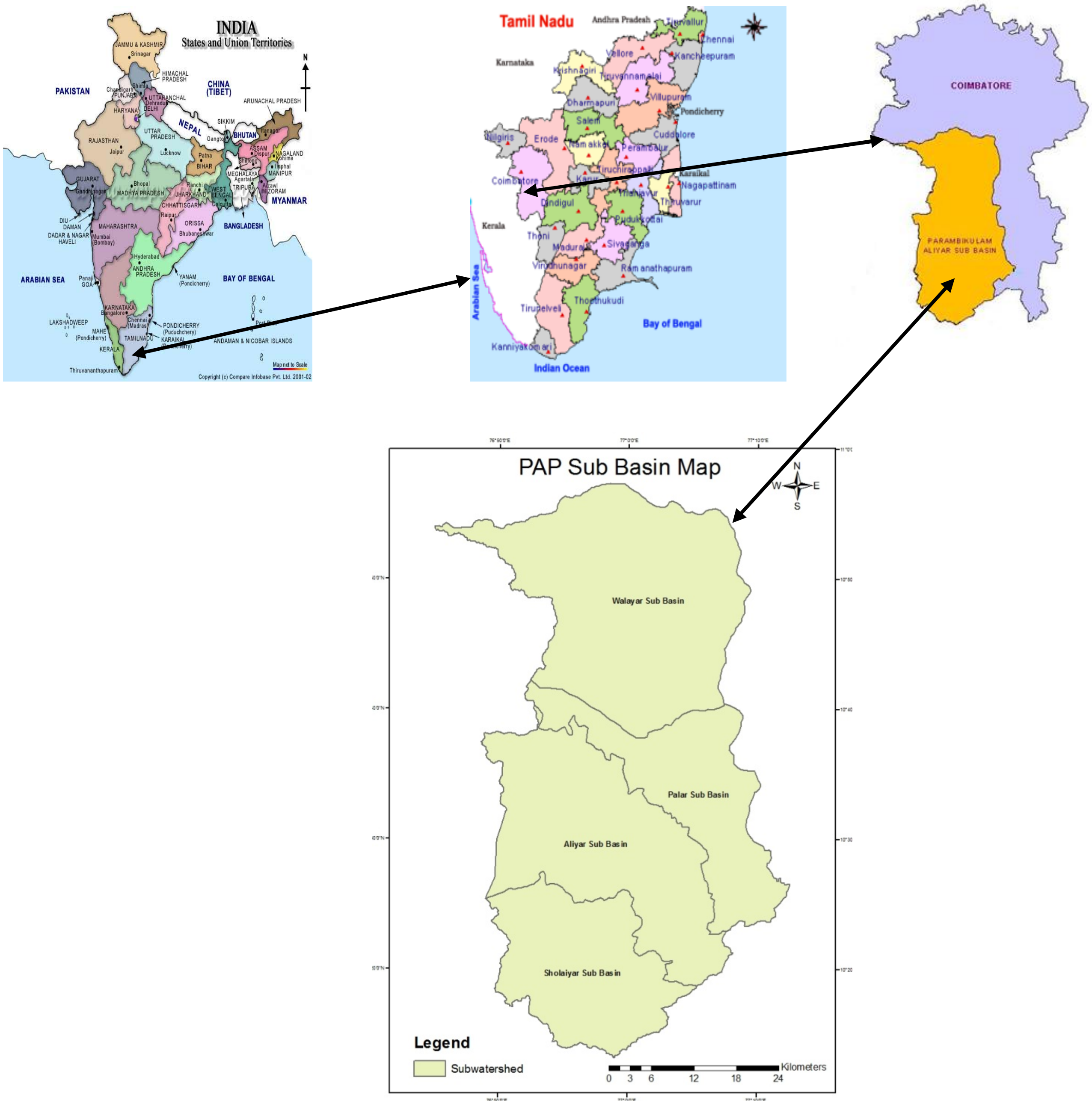

Fig.1. Location map of Parambikulam-Aliyar-Palar (PAP) basin
(Source: CGWB and PWD)

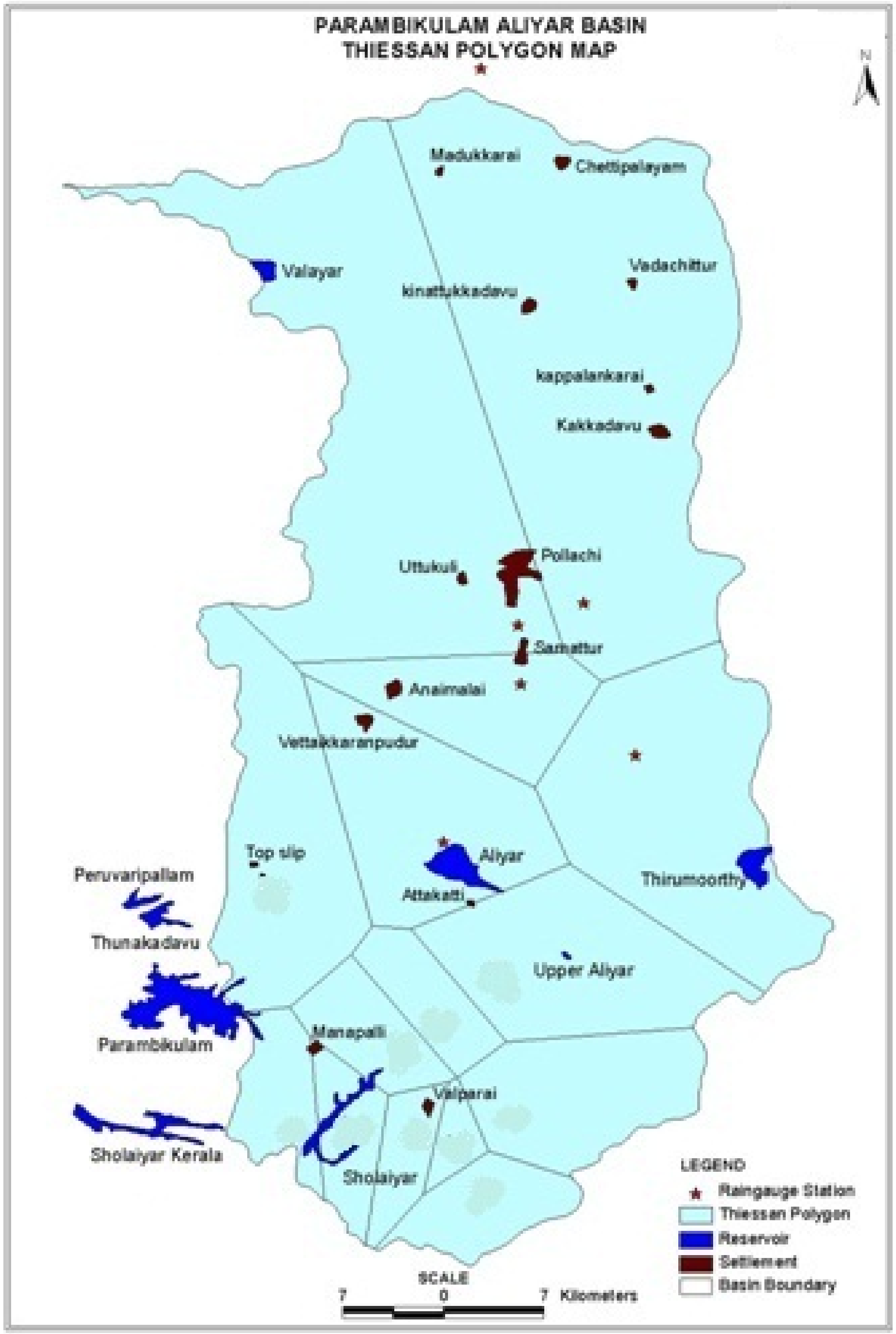

Fig.2. Thiessan polygon map showing the network of rain gauges in Parambikulam-Aliyar-Palar) basin

2. Methodology

2.1. Study Area

The location of observation wells and rain gauge stations in PAP are as shown in Fig. 2. For micro level study in PAP basin, 4(L) distributory of Pollachi canal coming from Aliyar reservoir was selected for this study. The total length of the Pollachi canal is

48 kms. The total command area under Pollachi canal is 9588.8 ha with 30 distributaries. The canal command is divided into two zones which receive water every alternate year. The distributory is located at an off take point of 5.2 km from the main canal. An attempt has been made to assess the surface, rainwater and groundwater availability of the study area and also to assess the irrigation water requirement (IWR) for the crops grown under different rainfall conditions, with an aim to plan accommodate and adapt for climatic extremes.

2.2. Rainfall Distribution

There are five rain gauge stations viz. Anamalai, Pollachi, Thirumurthy Nagar, Natakalpalyam and Aliyarnagar available in the basin. The average annual rainfall data (1988-2010) were collected and analyzed. Anamalai station recorded the highest average annual rainfall of 1372.1 mm followed by Aliyarnagar (871.3mm), Pollachi (830.3mm), Thirumurthynagar (722.3mm) and Natakalpalyam (534.5mm). It has been noted that the stations Anamalai and Pollachi received major portion of their annual rainfall during South West monsoon, while Aliyarnagar, Thirumurthynagar and Natakalpalyam received rainfall during North East monsoon. The rainfall analysis of five rain gauge stations in PAP basin showed a wide variation in the mean annual rainfall over the years (1988-2010) from the lowest of 210.6 mm (2003) to the highest of 5346.4 mm (2007). The mean annual rainfall for the period (1988-2010) was estimated to be 1372.1 mm. The area receives nearly 54.4 percent of annual rainfall during SW monsoon season (Jun-Sept) and 30.6 percent during NE monsoon season (Oct-Dec) and the remaining 15 percent rainfall during winter and summer seasons (Jan-May). Overall, the rainfall distribution pattern is highly stochastic and it can be inferred from the spatial and temporal variability data presented in Figs. 3 and 4.

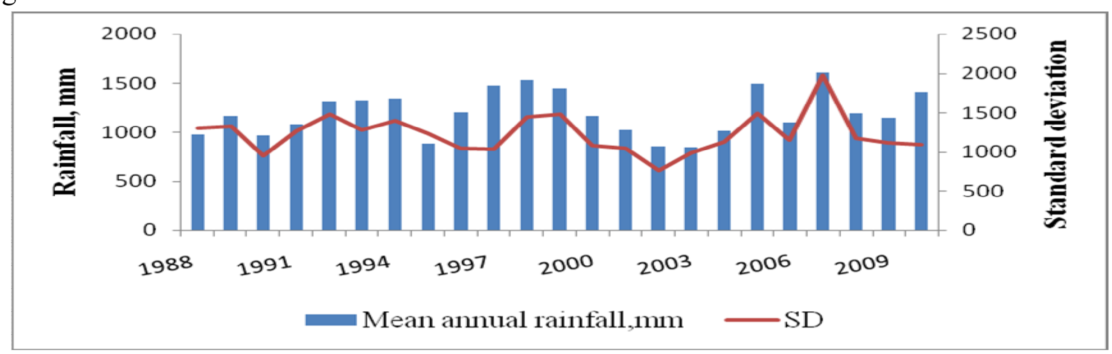

Fig. 3. Annual rainfall and standard deviation of the PAP basin(1988-2010)

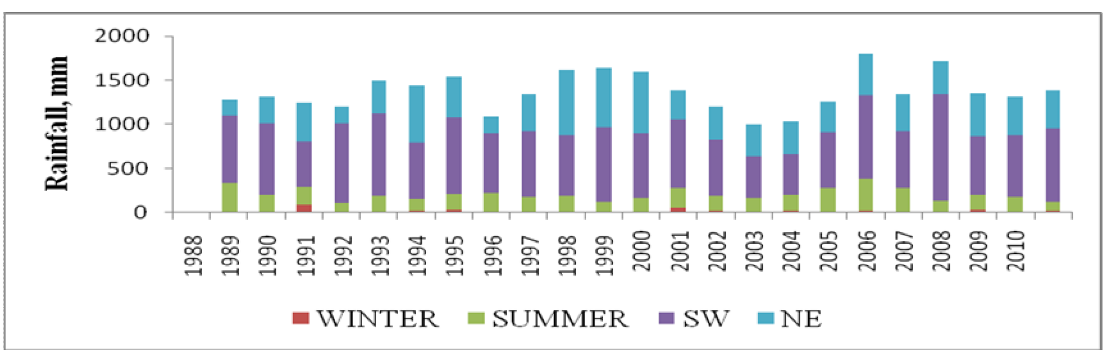

Fig.4. Seasonal average rainfall for winter, summer, SW and NE monsoon in the PAP basin from 1988-2010

The weighted mean rainfall for PAP basin using Thiessan polygon method was 1108.2 mm (Table 1). The Thiessan polygon method of calculating average rainfall over an area is superior to arithmetic mean as weights are assigned to each rain gauge in direct proportion to the area it represents and not to the total basin (Fiedler, F.R. 2003 & R.Suresh, 2005).

The annual and seasonal rainfall at probability levels of 50, 60, 70, 80 and 90 per cent were calculated by Weibull's method (Jayakumar et al.1995) for the study area from 1988-2010. The annual rainfall at 50, 60, 70, 80 and 90 per cent probability levels was found to be 1164.5, 1125.3, 1012.1, 973.6 and 870.3 mm, respectively. The probability of rainfall during winter (Jan-Feb) was almost zero and the highest rainfall occured during SW monsoon followed by NE monsoon (Fig 5).

The mean annual rainfall variability was shown in fig. 6. The results show that the highest mean annual rainfall of 1420 mm and the lowest mean annual rainfall of 580 mm accruing in 2007 and 2002, respectively.

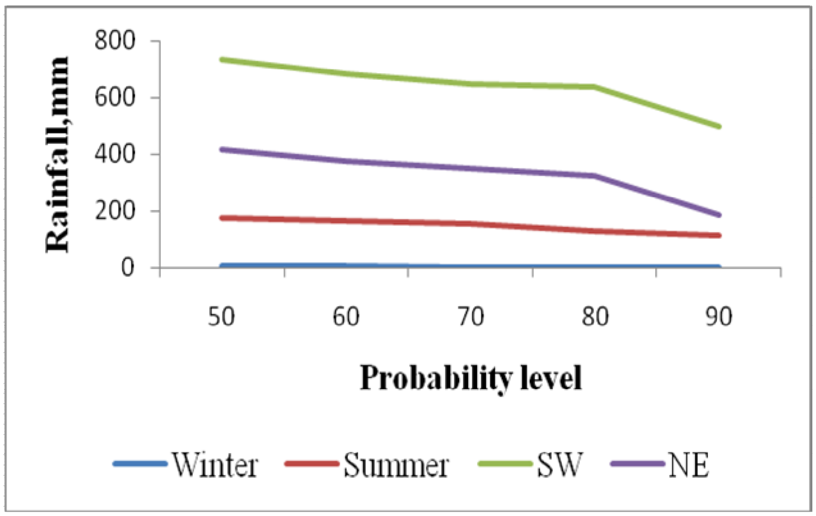

Fig. 5. Seasonal rainfall at different probablility levels

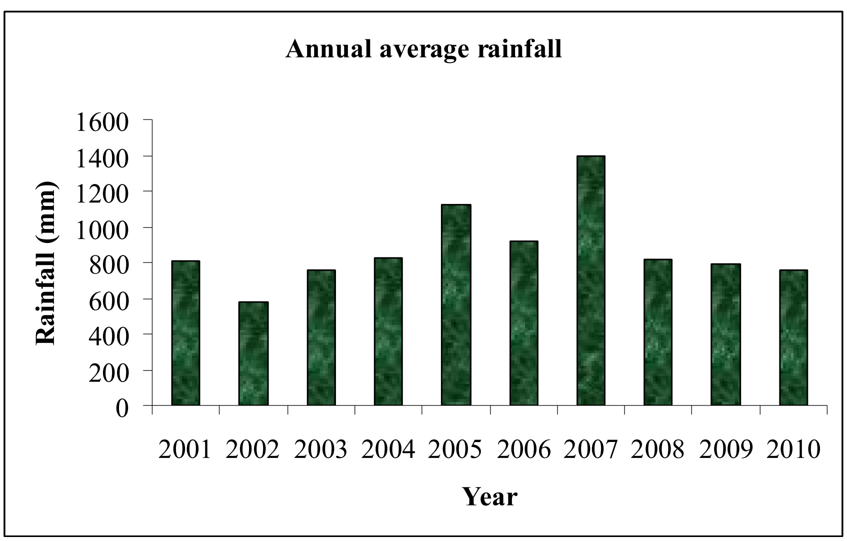

Fig. 6. Annual rainfall variability during 2001-2010

Table 1. Theissan polygon based weighted mean of rainfall distribution

Raingauge station	Aliyar nagar	Pollachi	Thirumurty nagar	Anamalai	Nattakapalayam	Total	Weighted mean rainfall, mm
Area, sq.kms	96.64	362.97	224.51	141.83	338.05	1164.00	
Jan (rainfall, mm)	9.92	6.39	13.11	9.58	5.93		
Area*rainfall sq.kms-mm	958.67	2319.38	2943.33	1358.70	2004.64	9584.71	8.23
Feb(rainfall, mm)	9.52	6.47	7.17	10.90	4.63		
Area*rainfall sq.kms-mm	920.01	2348.42	1609.74	1545.91	1565.17	7989.25	6.86
Mar (rainfall, mm)	26.54	28.57	14.69	58.42	17.28		
Area*rainfall sq.kms-mm	2564.83	10370.05	3298.05	8285.53	5841.50	30359.97	26.08
Apr (rainfall, mm)	73.83	55.37	55.23	121.23	51.52		
Area*rainfall sq.kms-mm	7134.93	20097.65	12399.69	17193.69	17416.34	74242.29	63.78
May (rainfall, mm)	72.71	70.53	50.70	191.81	56.01		
Area*rainfall sq.kms-mm	7026.69	25600.27	11382.66	27203.84	18934.18	90147.64	77.45
Jun (rainfall, mm)	75.60	73.15	34.15	664.71	11.45		
Area*rainfall sq.kms-mm	7305.98	26551.26	7667.02	94273.83	3870.67	139668.75	119.99
Jul (rainfall, mm)	110.90	170.89	46.30	1029.84	8.50		
Area*rainfall sq.kms-mm	10717.38	62027.94	10394.81	146059.12	2873.43	232072.67	199.38
Aug (rainfall, mm)	77.18	81.79	27.68	637.59	15.45		
Area*rainfall sq.kms-mm	7458.68	29687.32	6214.44	90427.48	5222.87	139010.78	119.43
Sep (rainfall, mm)	52.54	37.89	47.65	454.53	48.32		
Area*rainfall sq.kms-mm	5077.47	13752.93	10697.90	64464.63	16334.58	110327.50	94.78
Oct (rainfall, mm)	170.55	150.64	166.71	388.21	144.10		
Area*rainfall sq.kms-mm	16481.95	54677.80	37428.06	55058.66	48713.01	212359.48	182.44
Nov (rainfall, mm)	164.02	135.75	195.51	165.57	147.77		
Area*rainfall sq.kms-mm	15850.89	49273.18	43893.95	23482.30	49953.65	182453.97	156.75
Dec (rainfall, mm)	55.45	39.74	88.26	43.37	41.14		
Area*rainfall sq.kms-mm	5358.69	14424.43	19815.25	6151.04	13907.38	59656.78	51.25
Annual rainfall, mm							**1106.42**

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Coconut						Perennial crop						
Cotton		GS1	GS2	GS3		GS4	GS5					
G.Nut 1									GS1	GS2	GS3	GS4
G.Nut 2	GS2	GS3	GS4									GS1
Maize 1		GS1	GS2	GS3	GS4							
Maize 2						GS1	GS2	GS3	GS4			
Veg 1		GS1	GS2		GS3	GS4						
Veg 2						GS1	GS2		GS3	GS4		

GS1: Establishment stage GS2: Vegetation stage GS3: Flowering stage

GS4: Yield forming stage GS5: Ripening stage

Fig 7. Crop calendar in the 4 (L) distributory command area

2.3. Cropping Pattern

There are two cropping seasons in the areas which include irrigated crops during NE monsoon season (Season 1) and rainfed crops during SW monsoon season (Season 2). The study area receives 20 percent of annual rainfall between January to May, and the remaining 80 percent rainfall during monsoon season (June-December) with occasional long dry spells.

The soil in the command area is clay loam and is suitable for the cultivation of different types of crops. The crops grown at present are mainly coconut maize, cotton, groundnut and vegetables like tomato, brinjal, to name a few. All of these crops are grown during NE (October to December) and SW (June to September) monsoon seasons. The crop calendar of the study area is presented in Fig 7.

2.4. Canal Water Availability

The total number of canal running days ranged from lowest of 10 days (2003) to the highest of 149 (2007) days. During the years 2000, 2001, 2002, 2003 and 2004, the canal running days were less (10- 23 days only). The reason for less days of canal flow was attributed to low inflows into the reservoir due to deficit in rainfall during these years and also due to repair works in the canal system. However, there was an increasing trend from 2005 onwards with maximum of 149 canal running days in the year 2007. The details of monthly water release into 4(L) distributory from 2000 to 2010 were as shown in Table 2.

Table 2. Month wise details of canal water released into 4(L) distributory from 2000-2010 (ha m)

Year / Month	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Jun	1.53	0.89	0.24				1.57	7.38			
Jul			1.65					2.49			
Aug		0.00				8.59		4.47		5.21	
Sept		0.26			1.56	12.83	8.60	3.24		5.40	
Oct					1.12	12.42	13.06	4.45	8.66	12.62	9.27
Nov					1.96	6.79	7.06	5.38	8.68	3.27	5.92
Dec	0.74			0.76	1.69	0.44	14.07	7.77	11.29	11.21	
Jan	0.38	2.12	2.98	1.03	0.68	1.05	6.36	6.51	10.60	11.72	10.43
Feb	1.57	2.03	0.45	1.34	2.21	1.47				5.57	
Mar	0.68	1.60	4.01		1.09			1.84			
Apr	2.73	1.87	1.41	0.82			7.24				
May	1.67	1.29	0.29								7.54
Total	**9.30**	**10.1**	**11.0**	**4.0**	**10.3**	**43.58**	**57.96**	**43.55**	**39.23**	**54.99**	**33.16**

It is evident from the Table 2 that limited flows prevailed during 2000, 2001, 2002, 2003 and 2004 years. For calculating water available at field level, the seepage losses were calculated using wetted surface area and number of canal flowing days. For estimating the water available at the water courses, a further 10 percent reduction in the available water (as calculated above) was made and the balance was considered available at the field level. The evaporation losses from the free water surface in the water conveyance network were ignored. The details of canal water available at field level are furnished in Table 3, after accounting for all losses.

Table 3. Canal water available at field level (ha m)

Year	Canal water	Seepage losses	Water availability at distributory level	Water course losses 10 per cent	Water available at field level
2000	9.30	1.05	8.25	0.83	7.42
2001	10.1	1.15	8.95	0.90	8.05
2002	11.0	1.33	9.67	0.97	8.7
2003	4.0	0.46	3.54	0.35	3.19
2004	10.3	1.47	8.83	0.88	7.95
2005	43.58	4.21	39.37	3.94	35.43
2006	57.96	10.63	47.33	4.73	42.6
2007	43.55	6.83	36.72	3.70	33.02
2008	39.23	3.76	35.47	3.55	31.92
2009	54.99	6.00	48.99	4.90	44.09
2010	33.16	4.21	28.95	2.90	26.05

2.5. Irrigation Water Requirement

The irrigation water requirement for crop production is the amount of water, in addition to rainfall, that must be applied to meet crop evapotranspiration without significant reduction in yield. Exact amount of water required for different crops in a given set of climatological condition of a region is important for planning irrigation scheme, irrigation scheduling, effective design and management of any irrigation system. Bose and Kselic (1996) developed CRIWAR 2.0, a crop water irrigation requirement simulation model to estimate the crop water requirement of a cropping pattern in any irrigated area. The model is a helpful tool in the management of operational irrigation projects with frequently changing cropping pattern, and it can be used for performance assessment of any irrigation project. The model outputs could be used to identify the water requirements at the delivery structure on an irrigation command area. Considering the above mentioned aspects, an attempt was made to assess the irrigation water requirement for sustainability and maximize the net returns in selected distributory in Pollachi canal system of PAP basin.

The Aqua Crop3.1 model developed by Raes et al. (2011) is different from other existing crop models because of its accuracy, simplicity, and robustness. Aqua Crop has a structure that overarches the soil-plant-atmosphere continuum. It consists of five input components such as climate, crop, soil, field, and irrigation management. The details of crops grown in the command *viz.,* climate, soil data etc are used to assess the net irrigation requirement in the distributory.

The ETo Calculator, an evapotranspiration model developed by FAO was used to compute the reference evapotranspiration values. The model uses Penman-Monteith method to calculate the ETo values. The ETo values thus obtained are uploaded to Aqua Crop model. The effective precipitation is one of the water inputs to the soil root zone. For irrigation purpose the effective rainfall is defined as the part of total precipitation during the crop growing period that is available to meet the evapotranspiration needs of that crop. USDA Soil Conservation Service Method (USDA-SCS Method) is used by the crop model for calculating the effective rainfall.

According to this method the monthly effective rainfall can be calculated according to

$$ER= R\,(125-0.2*R)/125 \text{ for } R_{tot}<250 \text{ mm and} \quad (1)$$

$$ER= 125-0.1\,*R \text{ for } R_{tot}>250 \text{ mm} \quad (2)$$

The net irrigation requirement for crops grown in the distributory is computed by the AquaCrop3.1model. The net irrigation requirement (NIR) of a crop is the amount of water, in addition to rainfall, that must be applied to meet crop evapotranspiration (ETc) without significant reduction in yield. To avoid crop water stress, rainfall and irrigation must be sufficient to meet the crop ET requirement. Various methods are available to estimate the reference crop evapotranspiration (ETo). The crop evapotranspiration is calculated uses the following equation,

$$ET_c = K_c * ET_O \quad (3)$$

where,

ET_C= crop evapotranspiration (mm/day)

K_c= crop coefficient and

ET_O= reference evapotranspiration (mm/day)

The net irrigation requirement of crop can be estimated from the following equation,

$$NIR = ET_C - ER \quad (4)$$

where,

NIR = Net irrigation requirement in a given month, mm/month and

ER = Effective rainfall in a given month, mm/month

The NIR for crops grown in the study area from the year 2000 to 2010 were obtained by running the model for multiple years successively using Aqua Crop 3.1 model.

3. Results and Discussion (Modeling)

3.1. Assessment of irrigation water requirement

Assessment of crop water requirement for various crops is an important factor and basic requisite for crop planning in a command. As summarized before, the major area (199.3 ha) in the selected distributary was used for coconut plantation, which is nearly 80 percent of the total cropped area, whereas crops like cotton, maize, groundnut, tomato, brinjal were also grown in the remaining 20% area. The crop water requirement for years from 2000-2010 were calculated using Aqua Crop3.1 model. From the daily weather data, the monthly ETo values were calculated (2000 – 2010) using ETo Calculator developed by FAO. It can be seen that the monthly average reference evapotranspiration is highest during the month of May (7.36 mm/day) while, ETo value was minimum in the month of December (2.32 mm/day). Effective rainfall is one of the important water input to root zone to meet the evapotranspiration needs of the crop. The USDA soil conservation service (SCS) method was used to calculate the daily effective rainfall is presented in Fig.8.

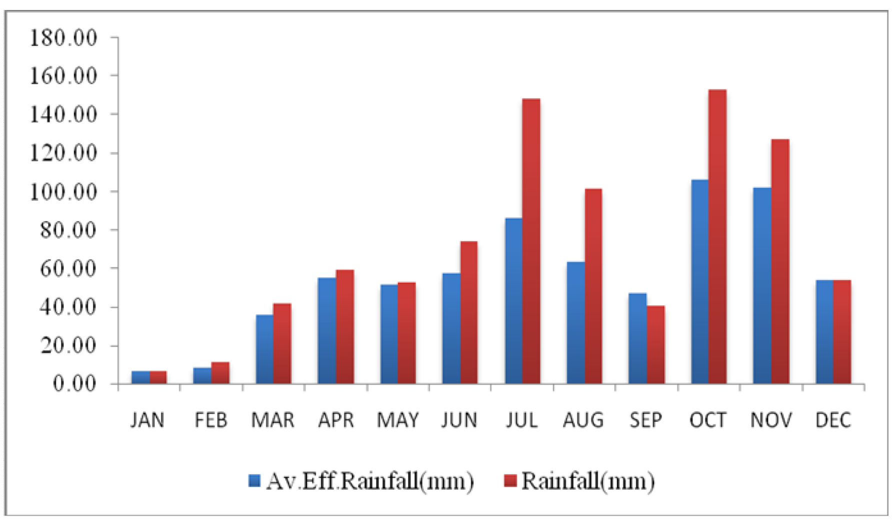

Fig. 8. Average monthly rainfall and effective rainfall predicted by the model for 2000-2010

The average annual effective rainfall (2000-2010) was calculated as 673.3 mm compared against annual mean rainfall of 876.3 mm

3.1.1. Normal

The monthly irrigation water requirements for crops grown in command area for normal rainfall year (2008) followed by excess rainfall year (2007) and deficit rainfall year (2002) are presented in Figs.9, 10 and 11.

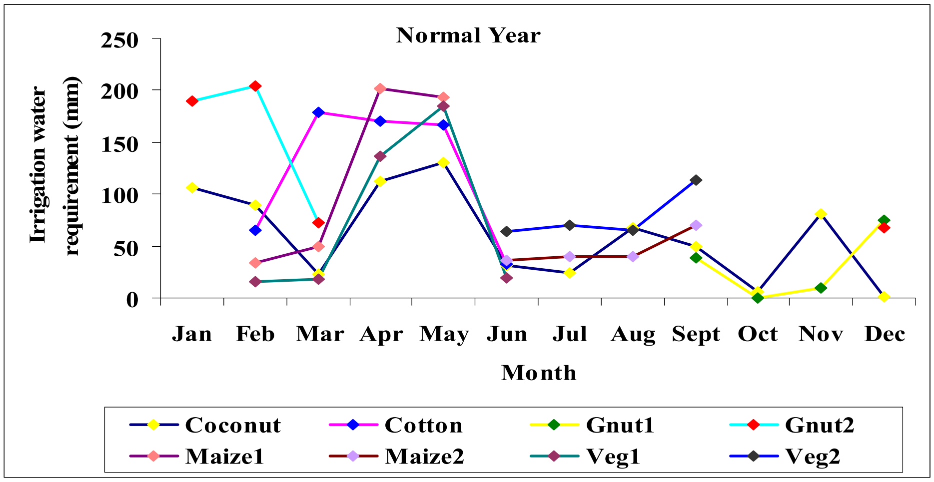

Fig.9. Monthly irrigation water requirement for crops grown in command area for the normal year (2008)

Higher water requirements during the months of April and May were 112.3 and 130.3 mm, respectively due to higher ET_0 values during summer months. The seasonal irrigation water requirement for Groundnut1 (Gnut.1) during (September-December) was less when compared to Groundnut2 (Gnut.2) grown in non-monsoon period. The rainfall received during NE monsoon (Oct- Dec) period was (331.6 mm) was sufficient to meet the water requirement with little supplemental irrigations. The water requirement for Groundnut2 (Gnut.2) was 533.6 mm due to less rainfall (34.3 mm) during January-March. Higher water requirements during vegetative and reproductive stages are beneficial for the crop. The crop water requirement for Maize1 were higher during the months of April (202.0 mm) and May (193.1 mm) (summer period) than February and March. Similarly, the water requirement during Maize2 (Jun-September) was less due to monsoon (258.5 mm) received during the period. Similarly, the irrigation water requirement for Vegetable1 (Veg1) was higher than Vegetable2 (Veg2) grown in monsoon period due to favorable climatic conditions prevailing during crop growth.

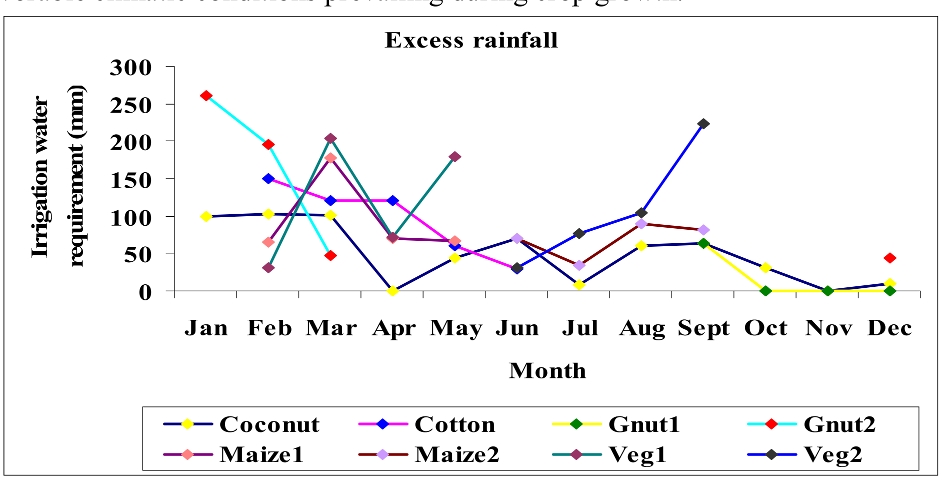

Fig.10. Month wise crop water requirement for crops grown in command area for the excess rainfall year (2007)

3.1.2. Excess Rainfall Situation

The irrigation water requirement for coconut was highest during the months of February and March but less during April and May due to rainfall received during these months. The irrigation water requirement was nil during November and it was just 9.3 mm during the month of December. The monthly water requirements in excess rainfall year (2007) were less when compared to normal rainfall year, 2008. The water requirement for coconut was 18.5 percent less when compared to 2007. The irrigation water requirement for cotton was 225.5 mm only due to rainfall (227.0 mm) received during crop period. The water requirement for Gnut1 was less due to uniform distribution of rainfall during NE monsoon period. The water requirement for Gnut2 in following season (December-March) was higher due to retrieval of monsoon. The reasons for variation in water requirement depends not only on rainfall but also climatic conditions such as temperature, relative humidity etc. Relative humidity will be less in monsoon period than in non-monsoon period resulting in less irrigation water requirement. The water requirements for Maize also follow the same trend. The water required for Vegetable 1 (Veg.1) (February-May) was 11 percent more than Vegetable 2 (Veg.2) grown in following season.

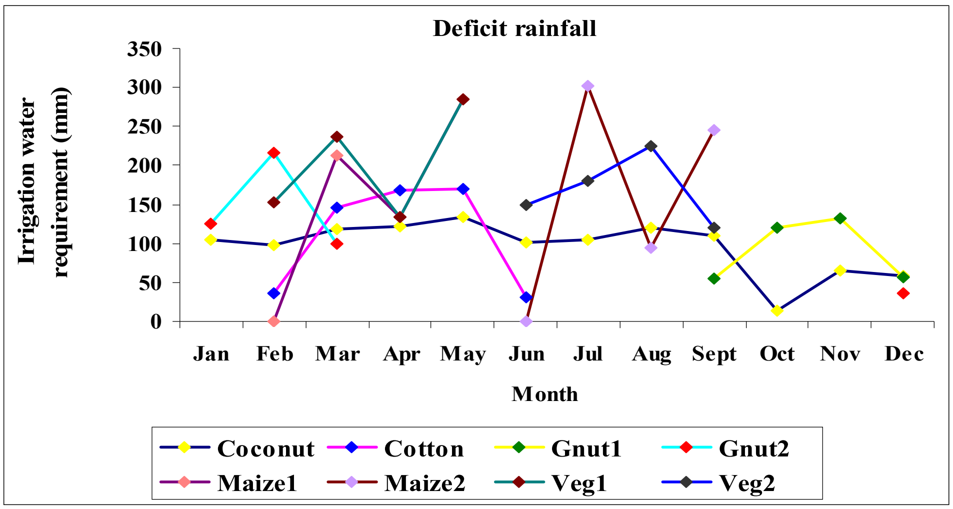

Fig.11. Month wise crop water requirement for crops grown in command area for the deficit rainfall year (2002)

3.1.3. Deficit Rainfall

The irrigation water requirement during the year 2002, (a deficit rainfall year) were higher compared to the years 2007 and 2008 are presented in Fig.10.The water requirement of coconut was 1150.2 mm with highest water requirement of 133.6 mm during the month of May due to higher ETo values. The higher water requirement for Groundnut1 (Gnut.1) crop season (365.3mm) during the year compared to normal (122.6 mm) and excess rainfall years (64.4 mm) reflects the failure of NE monsoon during 2002. Cotton grown in non-monsoon period consumes nearly 50 percent of total water requirement at flowering stage and boll formation stage. Higher irrigation requirements during this period will help in increasing the yields. Also the day temperatures of 25^{o}C and an average 12-13 hours of sunshine are favorable for obtaining optimum yields. An overall increase of 58.4 percent in water requirement was observed for the crops grown during 2002. The variations in irrigation water requirements for deficit, normal and excess years is shown in Fig.12.

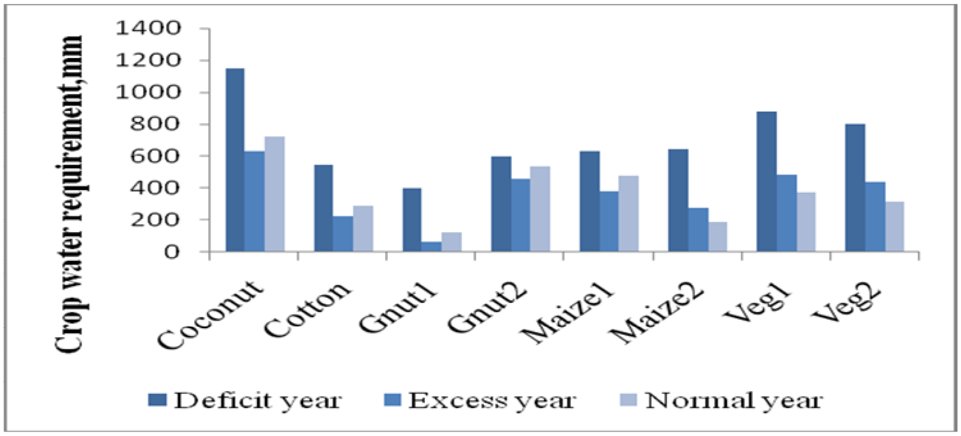

Fig. 12. Variations in irrigation water requirements in deficit, excess and normal years for crops grown in distributor

The average irrigation water requirements of the different crops during the years 2000 -2010, under existing cropping pattern are given in Fig.13.

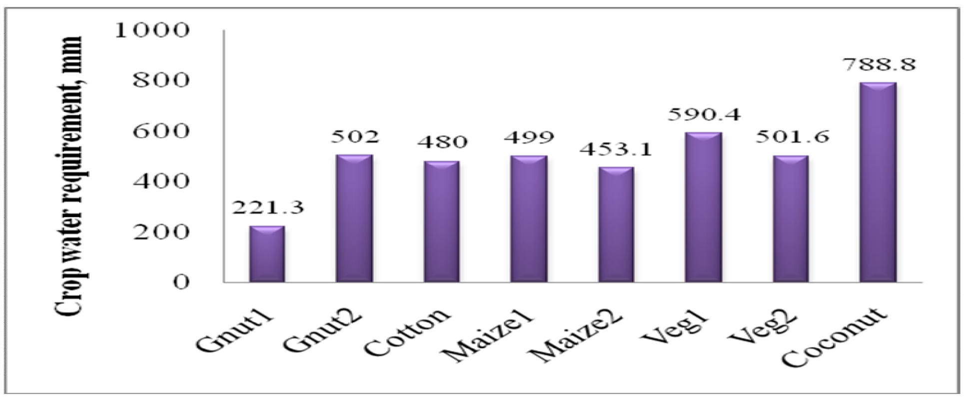

Fig. 13. Average irrigation water requirement for existing crops in the command area

The average irrigation water requirement for crops grown in monsoon period were less when compared to the crops grown during the non monsoon period.The average irrigation water requirement of coconut crop was nearly 788.8 mm with highest water requirement during 2001 and 2002 (1140.6 and 1150.2 mm, respectively) due to deficit rainfall during those years**.** The net irrigation requiremnt of cotton varied from 288.2 mm to 586.0 mm with lowest water requirement during 2008 due to dry soil moisture regime during crop growth period. The varaition in crop water requirement for Gnut1 and Gnut2 (221.3 mm and 502.0 mm) between the seasons is significant. The net irrigation requirement is almost doubled during non monsoon period due to retrival of rainfall during Jan-Mar. In Maize crop, being drought resistant did not show much significant variation in water requirement over the years in both seasons. Similarly, variation in water requirement was observed within seasons and also over years in Vegetable crops.The vegetable crops grown under irrigated conditions during Feb-Jun consumed more water than monsoon period crop (Jun-Sept).

4. Conclusion

The irrigation water requirement for the crops grown in the area was estimated using AquaCrop3.1model for the years 2000-2010. The total irrigation water requirement during deficit rainfall year (2002) was 58.4 percent higher compared to normal year (2008) due to high evapotranspirative demand of the crops.

Total water released from canal during the years 2000 to 2010 varied from 4.0 to 57.96 ha m for the distributory. Subtracting the seepage losses, the water available at distributory varied from 3.54 to 48.99 ha m considering the average conveyance losses of 10 per cent in the water courses, the water available at the field level varied from 3.19 to 35.43 ha m. The data revealed that the amount of water available by surface water supply is low, not sufficient to meet all the crop water requirements. The only means of meeting the crop water requirements is via additional rainfall or by exploiting local groundwater resources. The water course losses estimated varied from 0.35 ha m to 4.9 ha m over the years from 2000 to 2010. The variation was mainly due to the varying canal running days in a year. As per crop water requirements for an average year, the amount of water available in canal system is just $1/10^{th}$ of the total water requirement. Therefore, conjunctive use of water resources through judicious allocation of surface and groundwater resources could be an optimum approach to meet crop water requirements of the command area.

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A Review on Fluid Flow and Solute Transport Through Hard Rocks

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Abstract

This manuscript provides a review on fluid flow and solute transport mechanisms that are encountered in a typical hard rock system. It focuses on local-scale non-Darcian fluid flow and non-Fickian solute transport resulting from regional-scale, scale-dependent fluid flow (hydraulic conductivity) and solute transport (dispersivty) parameters. Since fluid flow and the resulting solute transport mechanisms can hardly be separated at any scale in a typical hard rock system, it is very critical to consider the local-scale physical, chemical and/or biological reactions and its associated fluid-rock interactions, for a reliable regional-scale groundwater model outputs. The aim of this review is to gather in a single article, both the fluid flow and solute transport aspects of a typical hard rock system that are conventionally considered either at a local scale and/or at the scale of a fracture network.

Keywords: Fluid flow; solute transport; hydraulic conductivity; dispersivity; fracture network; and hard rock.

1. Introduction

The water that is sequestrated and is flowing through soil or rock is referred to as groundwater and the movement of groundwater, along with the movement of water, from rest of reservoirs (atmosphere, ocean, lakes, streams and biosphere) in and around our planet describes the complete hydrologic cycle. Groundwater in Indian context is very precious as it contributes nearly 70% of irrigation water, and 85% of drinking water supplies. Further details from World Bank (2010) project that nearly 2/3rd of Indian groundwater resources will be in a critical state of degradation, within a next couple of decades. In addition, a recent survey by Government of India (GoI, 2010) has projected that water table decline exceeding 4 m is not uncommon in Indian scenario, which clearly indicates the unsustainable exploitation of groundwater in India. As a consequence, the quality of groundwater has also got deteriorated significantly, and eventually, has led to serious health concerns (Chakraborti et al., 2011). In this context, addressing the groundwater depletion scenario in Indian context is of prime importance, which subsequently, needs a sound understanding of fluid flow and solute transport in a typical groundwater system. Given the Indian scenario, where, nearly 2/3rd peninsular India is composed of hard rocks (including Deccan traps), a fundamental understanding of groundwater fluid flow and solute transport through hard rocks becomes inevitable.

The earth's crust, which can be conceptualized as the impervious rigid basements and forming the geologically most stable parts of the continents, predominantly consists of igneous (like granites, basalts and gabbros) as well as metamorphic (gneisses, schists and slates) rocks. On an overall vertical sequence of the earth's crust, the acid igneous rocks and metamorphic rocks are generally found very deep into the ground, where fractures/faults are relatively scarce, referred to as deep or massive zone; the basic igneous rocks can be found at a relatively shallower depth, especially under the marine beds, referred to as middle or fractured zone; while, the outcrops of igneous and metamorphic rocks, which approximately cover 1/5th of the earth's surface (nearly 30 million sq. km) is often enveloped by layers of sedimentary rocks, referred to as upper or weathered zone. Thus, the rock masses that are observed near the earth's surface are not essentially massive and consolidated, while they are subjected to enormous physical and chemical weathering, and subsequently, leads to discontinuities within the solid rock masses called fractures. Since, the solid rock masses, which are embedded in between the high permeable fractures, are highly impervious, the term "hard rocks" can safely be used as it essentially indicates a geological unit without sufficient primary porosity and conductivity for feasible groundwater extraction (Gustafsson, 1993). Thus, the water that diffused into the solid rock masses (primary porosity) and/or micro-cracks (secondary porosity) may not be drained out by gravity into the high permeable fracture, and subsequently, any storage and/or transmittance of groundwater within the solid rock masses, and across its boundaries is highly remote. Thus, in the context of hard rocks, it is these fractures or discontinuities (resulting from secondary porosities), through which the groundwater is stored as well as transmitted freely under gravity (zones of enhanced transmissivity), and this free groundwater is of interest towards water supply and/or water management problems. However, the importance of groundwater extracted from a hard rock towards water supply and management issues differ from place to place depending on its availability against demand. For example, unlike humid and temperate regions, arid as well as semi-arid regions depend heavily on groundwater resources resulting from insufficient surface water supply. The presence of fractures in such arid as well as semi-arid regions, form the most fundamental hydro-geological property of hard rocks, irrespective of their great variety of mineralogy, petrology and stratigraphy (Krasny and Sharp, 2003). These fractures, representing the preferential pathways, essentially control the groundwater fluid flow (hydraulic characteristics) and solute transport through hard rock masses. Thus, a fundamental understanding of fluid flow through hard rocks, and its associated solute transport becomes inevitable in applications such as disposal of high level nuclear wastes through hard rocks (post processes following the production of nuclear energy); multi-phase (gas, oil and water) fluid flow through fractured petroleum reservoirs (production of natural resources); multi-phase fluid flow (water and steam) through a fractured geothermal reservoir (production of thermal energy); and dewatering of mines; in addition to the conventional applications such as the water supply; groundwater recharge; migration of nutrients and chemicals through preferential pathways in vadose zones hard rocks; and, fate of pollutants in aquifers contaminated by agricultural, industrial and hazardous wastes in saturated zones of hard rock systems. In all of the above applications, the complex fluid velocity profiles in a hard rock system results in mixing of transported quantities such as mass and heat. In addition, the mass and heat exchange, accompanied by physical/chemical/biological reactions at the fluid – fracture-wall interface (fluid-solid interaction) significantly alters the nature of fundamental fluid flow and solute transport behavior in hard rock systems. However, it is extremely difficult to capture all the microscopic variations that essentially get translated into macroscopic mobility and spreading of solutes, considering the practical constraints. Thus, fluid flow and solute transport in hard rock systems, has been, and will be, an active area of research for years to come.

2. Rock Deformation and Fracture Generation

From a structural geological point of view, rocks found much deeper from the ground surface are very hot and tend to flow, while rocks at a relatively shallower depth are cool and tend to be more brittle. These relatively near-surface brittle rocks experience various external stresses such as tensional, compressional and shearing stresses, and, when these external stresses exceeds the internal strength of rock mass (yield strength), the rock mass starts yielding, and this physical process is referred to as deformation. This deformation is the effect, which is caused by brittle deformation of near-surface rocks. It can be noted that ductile deformation is associated with the formation of foldings such as anticlines, synclines, domes, and/or basin, and are found much deeper from the ground. Thus, the concept of hard rocks, in the context of groundwater fluid flow has no significance with the ductile deformation of rock masses. When brittle deformation occurs and rocks fracture, cracks are developed to produce a fracture, which is called a joint in the absence of an off-set, while the same fracture is referred to as a fault (vertical dip-slip or horizontal strike-slip fault) with an off-set. From a geo-mechanical point of view, a fracture, which essentially results from a rupture, can be defined as a surface in which a loss of cohesion has taken place. Further, a fracture is described as a fault, when the fracture planes had a relative displacement, while a fracture is described as a joint in the absence of any noticeable displacement of failure planes. A fracture, in general, can be defined as a discontinuity in a solid rock mass, which breaks a huge solid rock bed into a relatively smaller blocks along fissure / crack / fracture / joint / fault, and along which there is no displacement parallel with the planes of discontinuity. In a practical sense, a fracture can be considered as a joint or fault based on the scale at which a problem is being looked at. With reference to the history, the size and length of the fractures vary over a few microns in the initial stages. Once the rock mass encounters sufficient net imbalance in forces, resulting from mechanisms such as crustal-scale tectonic movements; heating and cooling of rock masses; and physical/chemical weathering, the rock's history experiences a brittle stage. During this stage, the rock mass undergoes enormous strain resulting from tensile, compressive and shear stresses, and eventually, deformation occurs as the external stress exceeds the yield stress of rock masses. At this stage, the resulting generated fractures are large, and very extended, and described as macro-fractures. In addition, these deformations do not occur uniformly over the entire rock mass of interest, while it gets concentrated at some locations depending on the nature and direction of the external stresses. Thus, the resultant deformation which exploits the planes of weaknesses in the rock masses, especially along the sedimentary bedding and metamorphic foliation, leads to the formation of secondary porosities or fractures. At this stage, the generated fractures are of limited extent, and with relatively small opening called micro-fractures or fissures. This deformation has varying intensity of fracturing (fracture density) as well as orientation depending on the locations of rock masses with brittle as well as ductile nature (Fisher and Wilkerson, 2000). These fractures further undergo geo-chemical (precipitation/dissolution) and/or geo-biological processes that alter the fracture aperture thicknesses. In all these cases, the complex internal structure of joints, deformation zones, and faults control the hydraulics of fluid flow. The joints, having a different strain level with reference to the fracture formation, are generally conceived to have parallel walled features, where the analogy of fluid flow through pipes can comfortably be applied. The thicknesses for both joints as well as tensile fractures generally vary over a few hundred microns. Andersson et al (2004) discussed the deformation zones in detail, where the thicknesses vary on the order of a few millimeters to several tens of centimeters. Caine et al (1996) discussed the faults in detail, where the thicknesses vary on the order of few centimeters to several tens of meters. Thus, a sound understanding of rock deformation helps to delineate the locations having a higher fracture density with significant fracture aperture thicknesses in a hard rock system. Above all, identifying the connectivity of complex network of fractures remains highly challenging, despite the details on the distributions of fracture length, fracture aperture thickness, fracture density, fracture spacing and fracture orientation. For example, an average higher fracture density with an average higher fracture aperture thickness and a relatively lesser fracture spacing might end up with a relatively lower effective permeability in the absence of proper connectivity of complex fracture network, while the total secondary porosity (including interconnected interstitial voids, fractures and dissolution discontinuities) would have significantly increased. Thus, there may be a clear mismatch between the enhancement in fracturing and the resulting effective hydraulic conductivity. Despite all these practical complications, the research on hard rock hydraulics, to meet the growing demands of groundwater supply, especially in arid and semi-arid regions of developing countries, remains extremely active.

3. Characterization of Rock Fractures

The presence of high permeable fractures in a typical hard rock system, essentially control the mechanical (stability and deformation) as well as the hydraulic properties (storativity and transmissivity) of rock masses. Identification of such fractures by non-invasive means is a tough task ahead. However, advancement in seismic imaging has allowed the geophysicists to identify both mega- and meso-scopic scale structures which are buried very deep into the ground and which does not have any surface impression. Interference analysis on the measurements of velocity and attenuation of elastic waves form the basis for surface and borehole seismic surveys.

It can be noted that this method has its own limitations resulting from inability to duplicate the in-situ conditions; as well as scale-dependence (limitation on continuum assumption) and frequency dependence (elastic attenuation) of rock properties. However, in the context of groundwater development, identification of fracture traces, especially using boreholes and wells, is widely used in characterizing a given hard rock system, as it subsequently allows the detection and characterization of permeable fractures, which control the groundwater movement in hard rocks. Several geo-physical studies have been made to delineate the presence of fractures in a hard rock system such as using borehole televiewer - BHTV (Zemanek et al., 1969), and electrical borehole scans (Luthi and Souhaite, 1990). However, these studies on fracture traces does not detail on the thickness of the fracture aperture, which is required for the computation of fracture permeability. For example, the fractures observed on BHTV logs may not be representing the entire fracture population, and also, these logs may not be directly related to conditions in the fracture away from the borehole wall, and eventually, cannot provide any information regarding the distribution of micro-cracks (Moos, 1983). Such earlier passive monitoring methods were associated with a relatively lower frequency, and eventually, the spatial resolutions were inadequate in characterizing the fracture details. For example, the transient Hydraulic Impedance Testing (HIT), based on the principle of wave propagation and reflection used a relatively lower frequency, around 10 Hz to characterize the boreholes (Holzhausen and Gooch, 1985; Holzhausen and Egan, 1986; Holzhausen et al., 1989), and this technique was widely used to determine the fracture closure pressures and dimensions, and this method is relatively inexpensive. Ashour and Yew (1996) extended the same approach to characterize the fractures using inverse Fourier transformation. Paige et al. (1995) improvised the earlier methods to better characterize the fracture length. Thus all the above methods were better suitable to investigate the local scale fracture details, while it remains insensitive towards characterizing a larger fracture network. Later, the concept of Vertical Seismic Profiling (VSP), associated with a relatively higher frequency (up to 100 Hz) provided an improved interpretation of surface reflection waves, especially in crystalline rocks. Following the advancement on check-shot surveys, VSP's have been used to calculate intrinsic attenuation (Ganley, 1981; Kennett 1981; Bouchen, 1981). The VSP has a better resolution in comparison with the surface seismic methods as both the sources as well as receivers are placed directly in hard rocks. However, VSP method may not be successful for mapping fracture zones in crystalline rock (Cosma et al., 2001). Cross-well seismic profiling has a still higher frequency (up to 250 Hz) than VSP, but works similar to VSP (Majer et al., 1997). Later, the concept of sonic logs came into picture, which is associated with high frequency range (up to 80,000 Hz). The sonic logs as are essentially continuous well velocity surveys as against the conventional surveys by check-shots. Gretener (1961) explained the velocity reduction associated with check-shot surveys using the concept of velocity dispersion. The sonic waves essentially combines the generation of surface waves along the borehole and the elastic waves of the rock formation, and subsequently, has a much better resolution than seismic waves. Using a source and a receiver array located in the borehole, the surface waves (Stoneley waves) generated from sonic log method critically delineates the fractures with significant aperture thickness, which actually contributes the fluid transmission (Brie et al., 1998; Gelinsky and Cheng, 1998). In essence, the sonic waves should have sufficient energy to get transmitted into the fracture, following which, the transmission as well as reflection coefficients are estimated based on the frequency used, and finally, the associated amplitudes and phases are analyzed critically, which decide the degree of fracture characterization.

4. Hard Rocks: An Aquifer or a Hydraulic Conductor?

Having delineated a geological unit with nearly planar discontinuities embedded within solid rock masses as hard rocks or fractured rocks (basic igneous rocks, metamorphic rocks and highly consolidated sedimentary rocks), an observation on its associated hydro-geological properties makes the hydraulics of fluid flow through hard rocks so complex as it varies enormously, often, within the same rock mass unit, and that too within short distances. Such complex fluid flow system places both experimentalists as well as modelers in difficulty as it is nearly impossible by field scientists to conduct all kinds of field experiments in hard rocks, while it is nearly a hypothetical system for the modelers who apply the very basic concept of continuum mechanics to understand the fluid flow through hard rocks. This is because the whole rock mass unit of interest does not get involved in transmitting its groundwater, unlike, what is observed in a classical porous system (where the Darcy flux is inversely related with the entire cross sectional area). In case of hard rocks, it is only through these high permeable fractures that the entire transmittance is associated with. It can also be noted the deviation of effective porosity from that of total porosity (when the hard rock mass and its associated fractures is considered as a single geological unit) vary over orders of magnitude in a typical hard rock system. Thus, the concept of fluid flow through a hard rock system fundamentally differs from that of a classical porous system in the sense that both storage as well as transmittance does not occur through the entire formation in hard rocks, unlike a classical porous system. In other words, the groundwater conductivity does not depend on the formation (primary porosity) itself as observed in a classical porous medium, while it depends on the geological structures (secondary porosity or fractures) that were developed much later than the formation porosity of hard rocks, and this concept raises questions against the usage of the term "aquifers" for hard rock systems. Hence, the usage of the term "aquifer" particularly in hard rocks deserves a special attention, while the term "hydraulic conductor" was suggested by Gustafson and Krasny (1993) in place of aquifers, for hard rock systems. This term includes the features such as single conductive fractures as well as fracture zones. In this context, any groundwater production from hard rocks is associated with at least one hydraulic conductor, and such hydraulic conductors can be identified by hydro-geological methods such as cross-hole pumping tests rather than from topographical inference or by geophysical methods.

5. Hard Rocks: Hydraulic Conductivity or Transmissivity?

On a general note, the hydraulic conductivity of fractures (the ability to transfer groundwater from one point to another through its interconnected fractures) tend to decrease with depth as in situ effective stress compresses the fractures, while the near surface fractures open up to a larger extent, associated with the physical and/or chemical weathering (Davis and Turk, 1964). Since the possibility of a greater number of interconnected fractures is highly remote in hard rocks, the degree of associated anisotropy is always on the higher side. In addition, in hard rocks, it is extremely difficult to conceptualize that the flow lines along the fractures are exactly perpendicular to the equipotential lines. For a homogeneous and isotropic pervious system, Darcy's law states that the hydraulic conductivity, which is the ratio between the specific discharge (measuring the intensity of fluid flow along the permeable interconnected void spaces) and the hydraulic gradient (measuring the rate at which the energy of the fluid flow decays along the flow direction), is a zero-order tensor, and provides, a scalar quantity, which means that the observation as well as prediction of hydraulic conductivity in space and time can comfortably be described at macroscopic-scale on a fictitious continuous system, and it implicitly captures all the heterogeneities, anisotropies and discontinuities influencing the hydraulic conductivity at microscopic scale. However, in hard rock systems with high degree anisotropy, heterogeneity and discontinuity, both the specific discharge as well as hydraulic gradient need to be considered as vectors (first order tensors), and eventually, the vector-to-vector ratio between them yields a second order tensor, requiring nine components in a three-dimensional rectangular Cartesian coordinate system. The Eigen values representing the non-zero main diagonal elements reflects the maximum, in between and minimum values of hydraulic conductivities along the principal axes (K_{xx}, K_{yy}, K_{zz}) respectively, while the Eigen vectors represent the three direction cosines, associated with the respective Eigen values. In the absence of these detailed values on hydraulic conductivities, the concept of "effective hydraulic conductivity" can be considered. However, as Gustafson (1986) pointed out, one needs several thousands of cubic meters of volume in order to deduce a stable value of effective hydraulic conductivity in hard rocks, and this particular issue questions the very applicability of continuum concept in hard rocks, as it is nearly impossible to deduce a Representative Elementary Volume of such a huge size, involving any hard rock system. And this is the reason why, the concept of fluid flow through a single fracture (a planar feature similar to a confined aquifer) at a local scale is still widely used. At a local scale, the variations in fracture aperture thicknesses (pore volumes or storage aperture times the area of each fracture) for a unit variation in hydraulic head provides the fracture storativity, while the variation in discharge through the fractures under unit hydraulic gradient and unit fracture width provides the fracture transmissivity. However, it is difficult to capture the variations in fracture storativity resulting from changes in fracture aperture (a measure of fracture's normal stiffness) and its associated changes in effective normal stress (a measure of compressibility of the pore fluid within a fracture). This ratio between transmissivity and storativity provides hydraulic diffusivity, which is a measure of the rate at which the hydraulic head propagates within a fracture. Since the fractures conduct almost all the fluids that it carries very efficiently, the associated fracture diffusivity values also are very high. A high diffusivity value represents a reduced time lag (Streltsova, 1988), and these diffusivity values helps in deducing the connectivity details of the fracture network (Knudby and Carrera, 2006). However, the issue of hydraulic conductivity in rocks attained further complexity after the introduction of Cubic law by Snow (1965), which states that the discharge through a parallel walled fracture varies as a function of cube of its fracture aperture thickness. As per this approach, a single fracture is conceptualized equivalent to a confined aquifer in a porous system, where the concept of transmissivity is applied as the product of hydraulic conductivity times the aquifer thickness. In hard rocks, this concept of "transmissivity" is more suitable over "hydraulic conductivity" as the fluid flow through a single fracture occurs over a unit fracture width rather over unit cross sectional area as followed in a classical porous medium. Thus, the hydraulic conductivity in hard rocks is indirectly computed by dividing the summation of transmissivity values measured from individual fractures that intersect a particular interval by the interval's length. This approach works well in the presence of a relatively higher fracture density, while for hard rocks with insignificant fracture density, this approach would yield different values of hydraulic conductivities for different interval lengths. In addition, the concept of specific discharge applied in a classical porous medium, which is a product of effective velocity and effective porosity, may not be applied directly in hard rock systems at the scale of a single fracture, and eventually, the concept of collinear vector quantities (effective velocity and specific discharge) does not arise in describing the fluid flow in a single fracture, as the porosity of a single fracture is 100 percent, and it is equivalent to fluid flow through pipes, where the conventional Navier-Stokes Equation is applied to describe the fluid flow through a single fracture, and Hagen-Poiseullie solution is deduced for a steady, incompressible, axisymmetric, fully-developed, laminar flow. It can be noted that when the fluid properties (density and viscosity) remain constant, the hydraulic conductivity is all about its permeability, which is a function of only rock properties. In addition, as Brace (1980) pointed out, when the temperature affects the fluid properties, which is more likely in hard rocks, the concept of permeability (m^2) is to be preferred to the hydraulic conductivity (m/d). In this context, "intrinsic fracture permeability" takes into account only fracture as its hydrodynamic unit, disregarding its associated solid rock mass (fluid flow through a cross section containing fractures only – single fracture or discrete fracture network approach); "conventional fracture permeability", which is based on classical Darcy's law takes into account both high permeable fracture as well as relatively impermeable solid rock mass as its hydrodynamic unit (fluid flow through a cross section containing both fracture as well as rock matrix – dual porosity approach); and, "permeability of a coupled fracture-matrix system" takes into account both high permeable fracture as well as significantly permeable solid rock matrix as its hydrodynamic unit (fluid flow through a cross section containing both fracture as well as rock matrix – dual permeability approach). The value of permeability can be measured either in the laboratory (using Darcy's equation) or in the field using well test analysis. It can be noted that when the well testing is done for a radial-symmetrical flow of a fluid towards a well under steady-state conditions, the magnitude of total permeability is measured, while the fraction of fracture and matrix permeabilities are not known explicitly. However, total permeability tends to approach the fracture permeability using Kazemi's conceptualization, where the matrix permeability is much lower than the fracture permeability (Kazemi, 1969); while, the total permeability again approaches fracture permeability using Warren and Root's conceptualization, where fluid flow occurs only through the regular fracture networks (Warren and Root, 1963). Thus, steady-state well testing yield a value of total permeability, which can be approximated to be equal to that fracture permeability, while a transient well testing is needed to measure the value of matrix permeability. Under such circumstances, the role of compressibility plays a crucial role as the porosity contrast between fracture and rock matrix is extreme. In addition, the values of fracture permeability, evaluated either from laboratory core test analysis or from field well testing data, have no correlation with the distribution of fracture length, fracture aperture, fracture density, fracture spacing and fracture orientation. Hence, in order to deduce a correlation between the fracture attributes and fracture permeability, a simulation of simplified fluid flow models are needed. If the resultant rock permeability (m^2) or the hydraulic conductivity (m/day) is significantly less (say, less than 10^{-6} m/s), then, the concept of "hydraulic fracturing" may be employed into those hard rocks, which essentially enhance the overall permeability of the reservoir, by inducing new artificial fractures. The earlier field tests on hydraulic fracturing have increased the well yield very marginally, despite having over two orders of magnitude increase in their respective hydraulic conductivities (Karundu, 1993).

6. Fracture Generations

Fracture detection is accomplished during the various operations such as drilling, logging, coring and testing, in both exploration and production phases of groundwater development in hard rocks. At this point, it is important to recollect the various terminologies that are usually used in the context of fracture network generation. A natural fracture is any break or crack occurring in the rock, while an induced fracture results during coring or from mishandling of cores. Measurable fractures are visible fractures and are described with reference to its fracture aperture, fracture length and fracture orientation (dip and strike angle), while non-measurable fractures are only traces across the core which end within the core, and hence, non-measurable fractures should not be used in deducing the fracture density and/or intensity. Similarly, macro-fractures are fractures with reasonable fracture aperture thickness (say, over 100 micro-meters) and significant length, while micro-fractures (also called fissures) have limited length and width. These smaller-scale micro-fractures with significant density might form a continuous fracture network, which is hydro-dynamically very similar to that of a classical porous medium. Open fractures mainly depend on circulating groundwater and rainfall, while closed fractures, which are essentially closed at the surface conditions might get opened up partially, whenever there is a significant pore pressure by the groundwater against the fracture walls. First-order fractures cut through several layers of rock, while second-order fractures are limited to a single layer of rock. Minor fractures are equivalent to second-order fractures, while average and major fractures are equivalent to first-order fractures. Further, fracture density represents the degree of rock fracturing, while fracture intensity represents the ratio between fracture frequency and layer thickness frequency (Racht, 1982). The fracture aperture thickness generally depends on the depth of the rock from the ground surface; the pore pressure exerted by the groundwater against the fracture walls; and, on the type of the rock material. The fracture aperture measurements carried out using core samples at the laboratory conditions might provide a lesser value with respect to its actual field value, due to the partial closure of fractures, related with the release of its accompanied confining and pore pressures.

The data on fractures can directly be collected either from a naturally/artificially exposed rock surfaces such as joints or from logging of borehole cores. The data gathered from local drill cores is more expensive and less representative of the large scale variations of fractures. Hence, to analyze fracture attributes, the study area is generally divided into a number of sub-domains in which around 5 – 30 sampling stations can be located, depending on the rock lithological and structural variations, and also, on the geometry and orientation of the underlying larger structures such as folds. Approximately around 50- 500 fractures are to be measured from each site, depending on the goals of the project as well as the type of the problems under investigation. Priest (1993) has described this procedure in detail, and has suggested two most widely used techniques of fracture measurement on exposed surfaces namely one-dimensional linear scanline, and two-dimensional areal scanplane. When several sets of fractures are present, the scanlines may be oriented perpendicular to the dominant fracture sets. In the event of having two scanlines, which are oriented perpendicular to the respective fracture sets, a third scanline may be oriented at about 45^{o} inclination to both of the scanlines. The trend and plunge of all the scanlines need to be recorded with the fracture data. In addition, at least two more scanlines, which are parallel and perpendicular to the geological unit, would ensure a more complete sampling of the three-dimensional volumetric distribution of fractures. Before any fracture characreristics data are gathered along the scanlines, information on stratigraphic and structural units are to be recorded, and the correction for the magnetic declination needs to be applied precisely. It can be noted that the surveys that only include the details of trend and plunge of the fracture traces in the absence of fracture planes details, will hardly provide any idea to the three-dimensional design of fractures.

7. Single and Multi-Phase Fluid Flows in Hard Rocks

Considering the fluid flow at micron level, between the fracture walls, the Reynolds number will still be less than unity in hard rocks as the characteristic fluid velocity (fluid velocity within high permeability fracture vary over 10 - 100 m/day) and the characteristic length (fracture aperture thickness vary over 10 – 100 microns) are well within the limits applicable to laminar fluid flow, where viscous forces still dominate. Hence, the concept of irrotational fluid flow resulting from vorticity of fluids along the rough fracture walls can be ignored considering the simplified conceptual model. In this approach, it is assumed that the flow is averaged over a Representative Elementary Volume (REV) containing several sets of fractures and rock-matrix blocks. Thus, it is possible to apply conventional Darcy’s law as the hydrodynamic unit consists of a huge hard rock volume. However, it can be noted that in this approach, the applicability of Darcy’s law remains a question as the porosity within the high permeability fracture is equivalent to 100%, and eventually, the concept of Darcy’s law, meant for a porous system, cannot be applied in the strict sense. It can clearly be noted that the concept of fracture porosity arises, only when, the entire hard rock unit is considered as a single hydrodynamic unit as against the single fracture approach. It is because of this reason the fluid flow within a single fracture is comfortably described by the simplified Navier-Stokes equation (Brush and Thomson, 2003). The first level of simplification assumes that the inertial forces in the flow field are insignificant with respect to the pressure and viscous forces (Tatomir, 2007). Louis (1969), among others, has experimentally proved that the onset of dominant inertial forces in fluid flow through a single parallel fracture starts approximately at a Reynolds number of 1200, and subsequently, justified the assumption of insignificant inertial forces. This simplification reduces the non-linear partial differential equation into a linear Stokes or creeping flow equations. The second level of simplification is associated with reducing the dimensionality of three-dimensional Stokes equation into two-dimensional equation, by assuming that the fluid velocity perpendicular to the parallel walled fracture is zero. Further, by incorporating the no-slip boundary condition at the fracture walls, the two-dimensional Stokes equation provides the velocity field within the fracture as a function of fracture aperture and hydraulic gradient. Substitution of this velocity vector in mass conservation equation yields the well known Local Cubic Law (LCL), where the fluid flow rate is proportional to cube of the fracture aperture, as against the conventional relation, where fluid flow rate is proportional to square of the mean grain size, and in turn, square of the voids or aperture. Further, at the scale of a single fracture, there is no distinction between Darcy flux and the mean fluid velocity. In addition, Singhal and Gupta (1999) have considered LCL for fractures with surface roughness. However, in reality, the fluid flow through fractures hardly follows the Darcian's theory due to the presence of high fluid velocity within the fracture under a relatively higher hydraulic gradient, and subsequently, it is difficult to justify the fluid flow to remain laminar and Newtonian; and frequently, the validity of no-slip boundary condition at the fluid-fracture interface also becomes a question.

In case of multi-phase fluid flow in a single fracture, the additional force called capillary pressure acting at the interface between the two immiscible fluids plays a major role, in addition to the pressure and gravity forces observed in a single-phase fluid flow. The same Darcy's equation is applied to describe the multi-phase fluid flow, where the absolute permeability is replaced by their respective effective permeabilities (for wetting and non-wetting phases), which is a product of absolute permeability and relative permeability. The summation of wetting and non-wetting phase saturations equals to unity, while the capillary pressure is assumed to be the difference in pressure measured at the interface between wetting and non-wetting fluids. Helmig (1997); and Bastian (1999) can be referred by the readers to look into the details on pressure, pressure-saturation, and saturation formulations. Brooks and Corey (1964) and Van Genuchten (1980) can be referred by the readers to look into the details on the variation of fluid saturation with capillary pressure as well as relative permeability. It can be noted that the fracture relative permeability curves of wetting and non-wetting phases would depend on the wettability of the fracture surface, and on the extent of interfacial tension between the immiscible fluids of interest. It can also be noted that in the absence of significant imbibitions forces, there will not be fluid mass exchange between fracture and rock-matrix, and subsequently, the multi-phase fluid flow may be restricted within the fracture network in a hard rock system.

In essence, the concept of ideal parallel plate fractures, where a mean value of fracture aperture is substituted in place of an actual rough walled aperture, as suggested by de Marsily (1986), poses fundamental problems in describing the multi-phase fluid flow through fractures as the capillary pressure reflects the interaction of fluid within the fracture and the rough walled fractures; and eventually, both the complex pore geometry of the fracture aperture; and the wettability characteristics of multi-phase pore fluids within the fracture play a crucial role, in addition to the interfacial tension that exists at the interface between the immiscible fluids. The problem gets further aggravated as the wettability in reality is mostly defined by a mixed wet, in which case, the saturation of fluid phases within the fracture varies as a function of both space and time.

Table 1. Gradual improvements in the conceptualization of groundwater fluid flow through hard rocks.

Nature of Geology	Continuum Concept	Permeability Distribution	Governing Equation
Roughly Homogeneous ignoring the presence of fracture traces (very far field)	Single	K	Darcy's Law
Heterogeneous aquifers with fracture sets (Concept of Equivalent Homogeneous-very far field) Pruess et al., (1986)	Single	$K_{effective}$ using arithmetic / geometric / harmonic means of K_f and K_m	Darcy's Law

Heterogeneous fractured aquifer (Single fracture / Regular fracture network-far field) Barenblatt et al. (1986); Warren and Root(1963);Huyakorn et al., (1983)	Dual	Explicit K_f and K_m with Instantaneous / Rate limited fluid mass transfer at the interface	Cubic Law from Navier-Stokes ignoring inertial effects
Heterogeneous fractured aquifer (Channel/Discrete fracture network- near/far field) Dershowitz et al (1999); Neretnieks (1993); Moreno et al (1997)	Dual/ Triple	Complex hydraulic characterization resulting from complicated distribution of rock and fluid properties of fracture & matrix leading to scale-dependent permeability	Complex equation which also includes fracture surface roughness, gravity effects and components of fluid velocity

It can be noted here that Tsang and Witherspoon (1981) and Brown (1987) have proved that the distribution and size of the fracture apertures have a significant impact on the resultant fluid flow within fractures, even in the absence of wettability effects. For example, when both wetting and non-wetting phase fluids are moving together in a multi-phase fluid flow system, the extension of single-phase Darcy's law to multi-phase fluid flow is applied to each phases individually (Dullien, 1992), and as a result, the permeability reduction resulting from the phase interference at the immiscible fluid interfaces remains unaccounted. And, this is the reason why, the sum of the relative permeabilities of wetting and non-wetting phases will always be less than one, especially at the intermediate fluid saturations. In addition, the investigations by Pruess and Tsang (1990); Rossen and Kumar (1992) have implied that the concept of multi-phase fluid flow remains meaningful only when the fracture aperture distribution is correlated as well as gravity segregation occurs. In addition, Bertals et al. (2001) strongly suggested that the concept of macroscopic capillary pressure based on local capillary equilibrium and Young-Laplace equation will be highly inadequate to describe the multi-phase fluid flow through fractures. It can be noted that under such circumstances, as pointed out by Blunt et al. (2002), the principle of mass conservation can be applied only when the fluid interfaces are assumed to be frozen, and eventually, the macroscopic properties such as relative permeability of the respective fluid phases are determined individually, without considering any interaction at the fluid inter-phases. Further, the above authors also illustrated that the relative permeability details deduced from pore-scale modeling could provide completely different results on multi-phase fluid flow from that of the conventional model predictions, based on macroscopic fluid flow. Thus, the challenge remains in up-scaling the pore-scale details to a larger field-scale multi-phase fluid flow in hard rock systems. To summarize, the gradual improvements in the conceptualization of groundwater fluid flow through hard rocks is provided in Table 1.

8. Solute Transport in Hard Rocks

Geological permeable media, particularly the hard rock masses are quite different from a classical porous medium in the sense that they are often fractured, and eventually, fluid flow and solute transport through such hard rocks can be quite different from that of the porous medium. Because most of the fluid flow occurs through the high permeability fractures, which are associated with relatively a higher average velocity with respect to that of porous medium, the associated mass as well as heat are also transported relatively faster. This relatively faster fluid flow; and, mass and heat transfer through a hard rock system, eventually leads to a relatively lower residence time within the rock fractures, and eventually, suppresses the fluid-rock interactions. This effect can have negative consequences in hard rock systems such as earlier arrival of high level nuclear wastes at the biosphere, and reduced geothermal reservoir efficiency. On the other hand, a relatively lower residence time of fluids within the rock fracture provides more opportunity to interact with the associated solid rock matrix, and in turn, the fracture aperture thickness may get significantly modified, resulting from physical/chemical/biological interactions that take place along the fracture walls. In addition, concepts such as fluid flow through preferential pathways (channeling); formation of fracture-skin along the fracture walls; solute mixing at fracture intersections; larger scale solute spreading resulting from fluid flow through multiple layers having contrasting aquifer properties (differential advection or macro-dispersion); peak mitigation of concentration fronts; skewed/extended tailing of break through curves; non-Fickian solute transport; and scale-dependent dispersivity, challenges the understanding of solute transport through hard rock masses. The readers can refer to the earlier review articles by Bear (1993), Neretnieks (1993), Bear et al., (1993) and Berkowitz (2002) for solute transport through single fractures, and Adler and Thovert (1999) for solute transport through a network of fractures. Understanding the transport of solutes in a three-dimensional fracture network system, which involves the local scale fluid-fracture interaction is extremely difficult. This is the reason why, various modeling approaches are being followed such as Discrete Fracture Network (DFN) approach, which ignores the details of local scale fluid-fracture interaction; Dual Porosity/Permeability approaches, which focus only on the local scale interactions between fracture and fluid; and Equivalent Porous Medium (EPM) approach, which considers the entire rock mass unit as a single continuum using the equivalent effective properties. The fundamental studies on solute transport through single fractures (Tang et al., 1981; Sudicky and Frind, 1982) were later extended to tracer test analysis by Maloszewski and Zuber (1993). The primary transport process advection, which involves the bulk movement of fluid flow, describes the transport of solutes, where the solute velocity equals the water velocity (obtained by dividing the flow rate through the fracture by its cross sectional area containing fracture aperture thickness and unit width). This process is denoted mathematically by first order partial differential equation of hyperbolic nature (first order wave equation), which essentially conserves the properties of the fluid during its transportation from one point to another. It can be noted that while solving hyperbolic equations, the errors that are committed during initial stages (say, from initial and/or boundary conditions), will be carried over with time as such, i.e., errors will be conserved; and this is the very reason why hyperbolic dominant equations remains challenging for numerical modelers. Dispersion is another major transport mechanism by aqueous/dissolved phase solutes. Taylor (1953, 1954) observed that the solute gets advected with the average fluid velocity in a circular pipe, while it simultaneously spreads at a rate which is inversely proportional to the molecular diffusion coefficient. To summarize, the gradual improvements in the conceptualization of groundwater solute transport through hard rocks is provided in Table 2.

Table 2. Gradual improvements in the conceptualization of groundwater solute transport through hard rocks.

Type	Nature of Geology	Continuum Concept	Dispersion Effect	Quantifying Longitudinal Dispersivity
Type I	Roughly Homogeneous ignoring the presence of fracture traces (Taylor, 1953; Aris, 1956)	Single	Micro-Dispersion as applied in Taylor-Aris dispersion.	One tenth of aquifer length

Type II	Heterogeneous aquifers with fracture sets (Concept of Equivalent Homogeneous) Dronfield and Silliman (1993); Ippolito et al., (1993); Anderson and Woessner (1992)	Single	Enhanced Micro-Dispersion resulting from fracture traces (roughness dispersion & aperture variation dispersion)	Little more than one tenth of aquifer length
Type III	Heterogeneous fractured aquifer (Single fracture / Regular fracture network) Haggerty and Gorelick, (1995); Bensen et al. (2000)	Dual	Macro-dispersion resulting from differential advection (Non-Fickian dispersion)	Significantly higher than the aquifer length
Type IV	Heterogeneous fractured aquifer (Discrete/Channel fracture network) Gelhar et al., (1992); Berkowitz and Scher (1997); Wu et al., (2004)	Dual / Triple	Complex dispersion characterization resulting from complicated distribution of fracture & matrix geometries leading to Non-Fickian dispersion	Much higher than the aquifer length resulting from complex mixing at fracture intersections in addition to micro- and macro-dispersion

This additional spreading/mixing/dispersion, in addition to the advective solute transport, results from the fact that the solute velocities encounter stream lines of varying velocities, while the solute diffuses along the flow direction. This coupled effect of simultaneous free molecular diffusion resulting from concentration gradient; and mechanical dispersion resulting from velocity variations put together referred to as Taylor's or hydrodynamic dispersion. It can be noted at this point that the magnitude as well as the characteristic time scale associated with the free molecular diffusion is much smaller than the magnitude and characteristic time scale associated with the mechanical dispersion. This concept of dispersion is exactly valid for a homogeneous and isotropic porous system, in the absence of heterogeneity and discontinuity. However, unlike in a classical porous medium, when describing transport of solutes through hard rocks, the role of free molecular diffusion, especially, along the fractures of few hundred microns is very crucial with reference to its associated mechanical dispersion. In fact, it is this free molecular diffusion that smoothen outs the concentration gradient perpendicular to the flow direction in describing transport of solutes in a single fracture, and subsequently, justifies the validity of one-dimensional assumption of solute transport in a single fracture. Aris (1956) extended the earlier works of Taylor, by providing an expression for evaluating the effective diffusion coefficient as a function of free molecular diffusion coefficient, using method of moments. This Taylor-Aris dispersion (also called micro-scopic dispersion) may not be directly extended to the solute transport in hard rock systems, as the solutes essentially diffuse into the solid rock matrix, while they may also get adsorbed within the huge rock-matrix volume. This distinction of fluid-rock matrix interaction leads to mitigated peak concentration, and extended/skewed tailing, depending on the magnitude of mass transfer coefficient. This mass transfer coefficient, which is a function of fracture aperture thickness (fracture geometry), effective matrix diffusion coefficient, matrix porosity, fracture fluid velocity and fracture roughness is considered as a coupling or sink term, in addition to the advective and dispersive transport of solutes along the fracture. The magnitude of effective diffusion coefficient depends on free molecular diffusion within the rock matrix and the tortuosity of the rock matrix. This coupling term collectively describes the depth (perpendicular to the fracture wall and flow direction) up to which, the solute will penetrate into the rock matrix, and also, specifies the rate at which the solute penetrates from fracture into the rock matrix. When this coupling term between fracture and rock matrix is of hyperbolic nature with huge gradients in the values of dependent (concentration) variables over a very short distance, similar to what is observed in a typical hard rock system at the fracture-matrix interface, the choice of numerical methods remains very sensitive. For example, in the case of finite difference approach, solving the mass transfer fluxes at the fracture-matrix interface remains challenging as this approach does not have any control over the value of the dependent variable between any two adjacent nodes (nodes just inside and outside the fracture over the interface). Finite element approach solves slightly better, but still, this approach also has disadvantage at the fracture-matrix interface in the sense that there is no control over the value of the dependent variables within any given triangular fracture element. This problem is very obvious when fracture-matrix interface cuts through triangular finite elements. It can be noted here that the value of the dependent variable is controlled only along the fracture element by appropriate trial/guess functions between adjacent nodes of interest. However, finite volume method provides an improved result, while solving the fluxes at the fracture-matrix interface as this approach is based on the principle of mass conservation, and the average value of the dependent variable of interest is deduced within any sub-cell or sub-volume by integrating the value of that dependent variable over the entire sub-volume; and any under-shoot or over-shoot encountered, resulting from huge gradients is corrected by applying appropriate limiters across the cell interfaces. This fluid mass transfer through fracture-matrix interface is described as matrix diffusion (Neretnieks, 1980; Birgersson and Neretnieks, 1990; Thoma et al., 1992; Wels et al., 1996; Haggerty et al., 2001). At a larger scale, the dispersion in network of fractures in a typical hard rock system depends on fracture morphology as well as fluid flow rate at the fracture intersections. Huseby et al. (2001) conducted simulation studies on a network of fractures and reported that both longitudinal and transverse disperse coefficients depend on Peclet number as a power with the same exponent, and this exponent depends on density of fractures. Retardation is yet another important transport mechanism, which essentially slows down the movement of solutes. Unlike a classical porous system, retardation in hard rocks results from matrix diffusion (solid-fluid interaction) also, in addition to the conventional linear/non-linear/equilibrium/rate-limited/kinetic adsorption observed in a mobile phase of the fluid. The adsorption, on the fracture walls on an aerial basis as well as adsorption within the solid rock matrix on the volume basis, is considered by their respective sorption distribution coefficients. However, caution must be exercised while applying the data captured from laboratory scale column studies to understand the retardation effects on a larger field scale problem as the complicated anisotropic, heterogeneous, discontinuous hard rock system can never be replicated at such a smaller laboratory scale. In general, this retardation is the cumulative effect resulting from fracture length, fracture aperture thickness, fracture roughness, type and nature of (altered) fracture wall material, matrix porosity, matrix diffusion coefficient, matrix tortuosity, type and nature of matrix minerals and fracture spacing. Rajaram (1997) introduced the concept of scale-dependent retardation factor by correlating hydraulic conductivity with retardation factor. Robinson (1994), and Reimus and Callahan (2007) have explained the concept of retardation in a dual porosity system, while Cvetkovic et al. (2004); and Frampton and Cvetkovic (2007) have investigated theses aspects using CTRW methods. It can be noted here that Continuous Time Random Walk method is an improved up-scaling approach to take into account the complexities such as multi-rate diffusion from high permeable fracture into low permeable rock matrix; varying fluid flow rates within the high permeable fractures of spatially varying cross sectional areas; and fractures of differing lengths (Geiger et al., 2010). Further, the equations developed by Deng et al. (2010) demonstrated that the scale dependency of reactive transport parameters were essentially associated with the spatial heterogeneity of reactive mineral facies.

In essence, the solute transport behavior in a hard rock system gets complicated because of the heterogeneous distribution of rock and fluid properties. As a result, the fundamental transport properties such as velocity and dispersion coefficients in a typical hard rock system remains no more a constant value, and varies as a function of both space and time. Although a number of researchers have worked on fluid and mass transport models at the scale of a single fracture, for example, Barenblatt et al., (1960); Warren and Root (1963); Bibby (1981); Huyakorn (1983); Leo and Booker (1996); Arnold et al. (2000); Litchner (2000); Mazurek et al. (2003); Qian and Zhan (2005); Wu et al. (2010); Haddad et al. (2012), the author preferred to outline his earlier works in detail, where the numerical modeling results have been extended to investigate the influence of spatial and temporal variation of the fundamental transport properties such as velocity, dispersivity and dispersion coefficient. Suresh Kumar and Sekhar (2005) developed a numerical model to study the transport of non-reactive solutes in a coupled fracture-matrix system using spatial moment analysis, and reported that both the velocity as well as dispersion varies as a function of time at an early stage (unlike a classical porous system), while the late time behavior replicated the transport behavior of a classical porous system. The authors also suggested that a given rock mass unit can be classified either into a porous system or hard rocks with the least number of fracture and matrix transport parameters namely fracture spacing, fracture aperture, matrix porosity and matrix diffusion coefficient. Later, Suresh Kumar and Ghassemi (2005) developed a numerical model to study the transport of reactive solutes under non-isothermal conditions, and investigated the spatial variation of fracture aperture thickness resulting from silica precipitation and dissolution. The same problem was further extended using spatial moment analysis (Suresh Kumar and Ghassemi, 2006), and their results suggested a non-Fickian behavior of solute transport, which eventually approached a Fickian behavior. Sekhar and Suresh Kumar (2006) deduced expressions for macro-dispersion coefficient at asymptotic regime as a function of effective local dispersion (which is similar to the dispersion mechanism observed in a classical porous medium), and an additional macro-dispersion resulting from fluid mass exchange between fracture and rock-matrix. Ghassemi and Suresh Kumar (2007) extended their earlier models to study the impact of thermal stresses associated with the solid rock matrix in the presence of silica precipitation and dissolution, and reported that the thermo-elasticity effect is dominant for smaller fracture apertures near the injection well. Suresh Kumar (2008) developed a numerical model to address the sorption non-linearity, and the influence of sorption intensities on dispersivity and macro-dispersion coefficient was investigated. The results suggested that the mixing of solutes was significantly lowered by non-linear sorptive behavior, with respect to the mixing caused by matrix diffusion for linearly sorbing solutes. The same author continued his model studies to investigate the influence of sorption intensity on solute mobility in hard rocks (Suresh Kumar, 2009), and the results suggested that the differing capacities of available sorption sites between fracture surfaces and solid rock matrix resulted in a slower migration of solutes along the fracture, accompanied with a larger amount of diffusive mass transfer. Natarajan and Suresh Kumar (2010) developed a numerical model for studying the transport of radio-nuclides in the presence of colloids in a coupled fracture-matrix system with fracture-skin at the interface, and analyzed the effect of colloidal dispersion coefficient and diffusion into the fracture-skin on colloidal migration. Later Natarajan and Suresh Kumar (2011a) further developed their model to study the transport of bacterial facilitated contaminants in a coupled fracture-matrix system, and their results suggested that there was significant bacterial concentration throughout the length of the fracture, when the sorption coefficient of bacteria on the fracture wall surface was very low. Natarajan and Suresh Kumar (2011b) studied the behavior of thermal fronts along the fracture in the presence of an additional heterogeneity in the form of fracture-skin in a coupled fracture-matrix system. Suresh Kumar et al. (2011) developed a numerical model and analyzed the mobility and spreading of decaying solutes in a coupled fracture-matrix system, and observed that the reduction in solute velocity was inversely proportional to the solute decay rate, while solute spreading followed a skewed Gaussian profile. Natarajan and Suresh Kumar (2012a) developed a numerical model to investigate the evolution of fracture permeability in a coupled fracture-matrix system in the presence of fracture-skin with simultaneous colloidal and bacterial transport, and by considering the thermo-elastic stresses by rock-matrix and its associated chemical reactions within the fracture in the form of silica precipitation and dissolution. Natarajan and Suresh Kumar (2012b) further developed their numerical model to investigate the transport of virus in a coupled fracture-matrix system in the presence of fracture-skin, and observed a decrease in virus concentration within the fracture as the fracture-skin properties were enhanced. Renu and Suresh Kumar (2012) developed a numerical model to investigate the mobility and mixing of solutes in a coupled fracture-skin-matrix system, and their simultaneous influence of non-linear sorption and radio-active decaying of solutes were investigated using spatial moment analysis. Suresh Kumar (2012) discussed the fluid dynamics aspects of sub-surface system in the context of hard rock hydrogeology, and the computational fluid dynamics aspects of non-isothermal reactive solute transport at the scale of a single fracture in detail. All the above studies at the scale of a single fracture strongly suggests that the fluid and mass transport processes along the high permeability fracture, and its associated fluid and/or mass exchange with its low permeability rock matrix (with fracture-skin) plays a very crucial role in determining the resultant skewed nature of the break through concentration profiles.

Table 3. Differences with classical fluid flow equations

Governing Equation	Darcy’s Law	Cubic Law
Scale	Macroscopic law used to describe fluid flow through a porous system	Microscopic law used to describe fluid flow through a pipe / capillary tube
Frictional Resistance	Insignificant kinetic head resulting from enormous frictional resistance	Significant kinetic head resulting from insignificant frictional resistance
Flow path	Highly tortuous	Streamlined
Flow rate	Proportional to square of aperture (mean grain size)	Proportional to cube of aperture
Fluid velocity	Darcy flux and seepage velocity are different and are connected by effective porosity	Darcy flux and seepage velocity are the same (for a single fracture with 100% porosity)
Porosity	Greater than zero and less than unity	Can be considered to be equal to unity
Permeability	Representative of entire geological unit	Representative of fracture unit only
Continuum	Single	Dual
Fluid-Rock interaction	No fluid exchange with the solid grains	Significant fluid exchange with rock-matrix depending on fracture and matrix pressure differences

Thus, the physical, chemical, and biological reactions leading to the concept of Non-Fickian behavior can comfortably be delineated from the studies on a single fracture. Having delineated the dominant physical, chemical, and biological parameters causing the Non-Fickian solute transport at the scale of a single fracture, the study of fluid and mass transport in a complicated network of fractures with its associated mixing characteristics at the fracture intersections remains highly challenging. Since the residence times associated with the fluid and mass transport within a hard rock system is significantly different at the scale of single fracture with respect to that of a fracture network, the modeling results by these two approaches may not necessarily imply the actual resultant fluid and mass transport, when the entire hard rock mass of interest is considered as a single hydrodynamic unit. On the other hand, since, it is nearly impossible to conduct experiments over a long period (say, several years), and also, since the size of the experimental setup cannot exceed over a few cubic meters (which cannot possibly represent a reliable REV), the investigations on fluid and mass transport in a typical hard rock system is heavily dependent on modeling studies, and subsequently, the interpretation of modeling results by various approaches leading to concepts such as Non-Fickian behavior and scale-dependent macro-dispersion coefficient and/or dispersivity needs utmost care. Table 3 provides basic differences observed when applying the governing fluid flow equations in a typical hard rock system.

9. Conclusion

Hard rocks, in general, outcrop and are affected by significant fracturing, through which circulation of groundwater takes place. Fluid flow and solute transport in hard rocks are important for problems of groundwater contamination, petroleum and geothermal energy production, and for several hydro-geological problems. Given the Indian scenario, where, nearly 2/3rd peninsular India is composed of hard rocks, a fundamental understanding of groundwater fluid flow and solute transport through hard rocks becomes inevitable. In the context of hard rocks, it is the fractures or discontinuities, through which the groundwater is stored as well as transmitted freely under gravity, and these fractures are of primary interest towards water supply and management problems. The primary hydro-geological parameter in hard rocks, hydraulic conductivity, needs to be considered as a tensor, and the concept of Representative Elementary Volume for the characterization of this parameter is extremely difficult, and subsequently, regional hydraulic properties are assumed to be a constant due to the availability of sparse data over dimensions of kilometers. In modeling hard rock systems, one needs several thousands of cubic meters of volume in order to deduce a stable value of effective hydraulic conductivity in hard rocks, and this particular issue questions the very applicability of continuum concept in hard rocks, as it is nearly impossible to deduce a Representative Elementary Volume of such a huge size, involving any hard rock system.

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Analytical and Numerical Approaches to Horizontal Non-reactive Solute Dispersion in a Semi-infinite Aquifer

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Abstract

The distribution of contaminant concentration along transient groundwater flow in a semi-infinite aquifer is derived by both analytical and numerical approaches. Initially, the concentration in the aquifer is considered space dependent with zero-order production term. The aquifer is subjected to time-dependent point source concentration at one end and at the other end the concentration gradient is supposed to be zero. The Laplace transform technique is applied to derive the analytical solution for the concentration distribution by assuming the aquifer to be homogeneous. The finite difference explicit method is employed to obtain the numerical solution if the aquifer is heterogeneous. The effect of decay term is also considered in the solution. The solutions for horizontal non-reactive solute dispersion in the aquifer are derived under two time-dependent flow velocities. It is assumed that the dispersion is directly proportional to seepage velocity.

Keywords: Solute Transport; Groundwater Contamination; Zero-Order Production Term; Transient Velocity; Analytical and Numerical Solution; Aquifer

1. Introduction

Over the years, there has been a considerable interest in the migration of solutes in groundwater. There are a multitude of problems, including groundwater contamination, seawater intrusion in coastal aquifers, radioactive waste disposal, geothermal energy development, groundwater-surface water interaction, and subsurface storage of materials and fluids, that involve solute transport. There seems to be an ever increasing pressure on the waste assimilating capacity of water resources in India. Contamination of groundwater by various types of waste disposal has become a serious environmental concern in recent years (Sharma and Reddy, 2004; Rausch et al., 2005; Thangarajan, 2006).

The remediation of groundwater contamination usually requires a quantitative description of the distribution and fate of contaminants. Mathematical model scan be employed to solve the advection/dispersion equation either analytically or numerically for the distribution and fate of contaminants. The advection-dispersion equation is derived, based on the principle of conservation of mass and Fick’s law of diffusion. If the medium is porous then it also satisfies Darcy’s law. This equation is widely used in describing the distribution of pollutants in aquifers, rivers, lakes, streams and oil reservoirs.

To date, many analytical models have been developed for simulating solute transport under different initial and boundary conditions (Ebach and White 1958; Ogata and Banks 1961; Al-Niami and Rushton 1977; Marino 1978; Sharma and Reddy 2004; Rausch et. al. 2005; Kumar et. al. 2006; Singh et. al. 2008, 2009). A number of investigations have considered groundwater velocity as steady (Aral and Tang 1992; Serrano 1995). van Genucheten and Alves (1982) reviewed non-dimensional conventional dispersion in steady flow through porous media. Banks and Jerasate (1962) derived a solution by assuming linear and exponentially decreasing time dependent expressions for seepage velocity through porous media. Analytical solutions were developed by Yates (1990) for transport of dissolved substances in uniform flow in heterogeneous semi-infinite porous media with a distance-dependent dispersion of exponential nature. Logan (1996) extended this work by including adsorption and decay. A one dimensional analytical solution was presented by Zoppou and Knight (1997) and Jaiswal et al. (2011) for the advection–diffusion equation, with solute dispersion being proportional to the square of velocity and velocity being proportional to the position. Aral and Liao (1996) solved the two-dimensional advection–diffusion equation by assuming time dependent dispersion along uniform flow. The solution of the advection–dispersion equation in cylindrical coordinates in a radially convergent flow field was derived by Chen et al. (2003) by applying a Laplace-transform power series technique. These analytical solutions are available only for relatively simple problems, i.e., the geometry of the aquifer must be regular. However, analytical solutions are virtually impossible for irregular boundary shapes due to the spatial variability of the coefficients appearing in the governing equation and the boundary conditions, the non-uniformity of initial conditions and the non analytical form of various sources.

The finite difference method is the oldest numerical method to solve partial differential equations (Southwell 1940; Forsythe and Wasow 1960; Fox 1962). In recent years, other powerful numerical methods have been developed, but due to simple basic theory, less computer memory and less computation time, the finite difference method is still preferred. The application of finite difference methods to solute transport modeling has been studied by relatively few researchers. The solute dispersion along unsteady groundwater flow in a semi-infinite aquifer was investigated by Kumar and Kumar (1998) where the solution was also derived by a finite difference method, assuming the dispersion coefficient and groundwater velocity were spatially dependent. Rouholahnejad and Sadrnejad (2009) studied the numerical simulation of leachate transport into groundwater at landfill sites. Ataie-Ashtianiet et al. (1999) analyzed truncation errors in finite difference models for solute transport equation with first-order reaction in which the analytical solution was compared with numerical solutions for a one dimensional case. Ataie-Ashtianiet et al. (1996) presented a numerical correction for the finite-difference solution of the advection-dispersion equation with reaction. The stability analysis was also discussed and the solution was compared with the analytical solution.

The present work describes one-dimensional solute dispersion in unsteady groundwater flow in a semi-infinite aquifer. Initially, groundwater is not solute free due to some internal cause or effect in the aquifer; therefore, the space dependent concentration with zero order production term is taken into consideration. The input concentration at the origin (where the pollutants reach the groundwater level) is taken to be of pulse type as reported by Kumar (1983). However, it is possible that the source of contaminants in the aquifer exists for a long time and it decreases with time; therefore, the time-dependent form of input concentration is considered to be with an exponentially decreasing unsteady velocity distribution. The effect of decay term is also considered in the solution. Due to the rise and fall of groundwater table, the groundwater flow is considered unsteady. In tropical regions, the groundwater level and velocity are at maximum in winter, after the rainy season and minimum in summer, just before the rainy season; therefore a sinusoidally varying velocity distribution is considered. The dispersion coefficient is considered to be directly proportional to the seepage velocity (Kumar 1983). The solution is derived for homogeneous and heterogeneous aquifers by analytical and numerical approaches.

2. Mathematical Formulation

Consider an isotropic aquifer that has space dependent initial concentration. Pollutants from point sources, such as septic tanks, garbage disposal sites, and cementation on the surface, infiltrate to groundwater and spread along the flow. The partial differential equation describing the distribution of solute concentration due to dispersion and advection in one dimension with a zero order liquid phase source can be written as

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left[D \frac{\partial c}{\partial x} - uc \right] + \gamma \tag{1}$$

where $c\ [ML^{-3}]$ is the solute concentration of contaminants in the aquifer, $u\ [LT^{-1}]$ is the groundwater velocity at position x at time t, $D\ [L^2T^{-1}]$ is the dispersion coefficient at time $t\ [T]$, and $\gamma\ [ML^{-3}T^{-1}]$ is a zero order production term.

Initially, groundwater is not solute free due to some internal cause or effect in the aquifer. Therefore, an appropriate initial condition may be chosen as

$$c(x,t) = c_i + \frac{\gamma x}{u},\ x > 0,\ t = 0 \tag{2}$$

For the input concentration at the origin, where pollutants reach the groundwater level, the first boundary condition is defined as

$$c(x,t) = \frac{c_0}{[1 + \exp(-qt)]},\ t > 0,\ x = 0 \tag{3}$$

The other boundary condition for a semi-infinite system can be defined as

$$\frac{\partial c}{\partial x} = 0,\ x \to \infty,\ t > 0\ . \tag{4}$$

where, $c_i\ [ML^{-3}]$ is the initial concentration and $c_0\ [ML^{-3}]$ is the solute concentration.

3. Dispersion along Homogeneous Aquifer: Analytical Approach

For a homogeneous aquifer, D and u are independent of x, the partial differential equation (1) can be written as

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} - u\frac{\partial c}{\partial x} + \gamma \tag{5}$$

where, $$u = u_0 f(mt) \tag{6}$$

The dispersion coefficient as directly proportional to velocity can be written as

$$\left.\begin{aligned} D\alpha u,\ D = au \quad D = au_0 f(mt) \quad D = D_0 f(mt) \\ and \quad \gamma = \gamma_0 f(mt) \end{aligned}\right\} \tag{7}$$

where, a is a coefficient of dimension of length and depends upon pore system geometry and on the average pore size diameter of the aquifer, D_0 is the initial dispersion coefficient, and γ_0 is the initial zero order production term.

Using equations (6) and (7) in equation (5), we have

$$D_0\frac{\partial^2 c}{\partial x^2} - u_0\frac{\partial c}{\partial x} + \gamma_0 = \frac{1}{f(mt)}\frac{\partial c}{\partial t} \tag{8}$$

Introducing a new time variable T^* by the following transformation (crank 1975)

$$T^* = \int_0^t f(mt)\,dt \tag{9}$$

Equation (8) can now be written as

$$\frac{\partial c}{\partial T^*} = D_0 \frac{\partial^2 c}{\partial x^2} - u_0 \frac{\partial c}{\partial x} + \gamma_0 \tag{10}$$

The initial and boundary conditions (2) to (4) become

$$c(x, T^*) = c_i + \frac{\gamma x}{u}, \qquad x > 0, T^* = 0 \tag{11}$$

$$c(x, T^*) = \frac{c_0}{[2 - qT^*]} \qquad T^* > 0, x = 0 \tag{12}$$

$$\frac{\partial c}{\partial x} = 0, \; x \to \infty, \; T^* > 0 \tag{13}$$

Now, non- dimensional variables are introduced:

$$C = \frac{c}{c_0}, \; X = \frac{x u_0}{D_0}, \; T = \frac{u_0^2}{D_0} T^*, \; \gamma^* = \frac{\gamma_0 D_0}{u_0^2 c_0}, \; Q = \frac{q D_0}{u_0^2} \tag{14}$$

Using equation (14), equation (10), together with equations (11)-(13), become,

$$\frac{\partial C}{\partial T} = \frac{\partial^2 C}{\partial X^2} - \frac{\partial C}{\partial X} + \gamma^*, \tag{15}$$

subject to

$$C(X,T) = \frac{c_i}{c_0} + \gamma^* X, \qquad T = 0, \; X > 0,$$

$$C(X,T) = \frac{1}{[2 - QT]} \qquad X = 0, \; T > 0 \tag{16}$$

i.e. $$C(X,T) = \frac{1}{2}\left[1 + \frac{QT}{2}\right], \qquad X = 0, \; T > 0, \tag{17}$$

and, $$\frac{\partial C}{\partial X} = 0, \; X \to \infty, \; T > 0. \tag{18}$$

Using the transformation,

$$C(X,T) = K(X,T)\exp\left(\frac{X}{2} - \frac{T}{4}\right) \tag{19}$$

and equation (15) reduces to

$$\frac{\partial K}{\partial T} = \frac{\partial^2 K}{\partial X^2} + \gamma^* \exp\left(\frac{T}{4} - \frac{X}{2}\right) \tag{20}$$

with the initial and boundary conditions

$$K(X,T) = \left(\frac{c_i}{c_0} + \gamma^* X\right)\exp\left(-\frac{X}{2}\right), \quad T = 0, \; X > 0, \tag{21}$$

$$K(X,T) = \frac{1}{2}\left[1 + \frac{QT}{2}\right]\exp\left(\frac{T}{4}\right), \qquad X = 0, T > 0, \tag{22}$$

and, $$\frac{\partial K}{\partial X} = -\frac{K}{2}, \quad X \to \infty, \; T > 0 \tag{23}$$

Taking Laplace transform and its inverse in equations (21) - (23), the solution can be written as

$$K(X,T)=\frac{1}{2}\left(\frac{1}{2}-\frac{c_i}{c_0}\right)\left\{\exp\left(\frac{T}{4}-\frac{X}{2}\right)erfc\left(\frac{X}{2\sqrt{T}}-\frac{\sqrt{T}}{2}\right)+\exp\left(\frac{T}{4}+\frac{X}{2}\right)erfc\left(\frac{X}{2\sqrt{T}}-\frac{\sqrt{T}}{2}\right)\right\}$$
$$+\frac{Q}{8}\left\{\begin{array}{l}(T-X)\exp\left(\frac{T}{4}-\frac{X}{2}\right)erfc\left(\frac{X}{2\sqrt{T}}-\frac{\sqrt{T}}{2}\right)+(T+X)\exp\left(\frac{T}{4}+\frac{X}{2}\right)\\ erfc\left(\frac{X}{2\sqrt{T}}-\frac{\sqrt{T}}{2}\right)\end{array}\right\}$$
$$+\left(\frac{c_i}{c_0}+\gamma^* X\right)\exp\left(\frac{T}{4}-\frac{X}{2}\right)$$

and applying the transformation given in equation (19) we can get the solution as follows:

$$C(X,T)=\frac{1}{2}\left(\frac{1}{2}-\frac{c_i}{c_0}\right)\left\{erfc\left(\frac{X}{2\sqrt{T}}-\frac{\sqrt{T}}{2}\right)+\exp(X)erfc\left(\frac{X}{2\sqrt{T}}-\frac{\sqrt{T}}{2}\right)\right\}$$
$$+\frac{Q}{8}\left\{(T-X)erfc\left(\frac{X}{2\sqrt{T}}-\frac{\sqrt{T}}{2}\right)+(T+X)\exp(X)erfc\left(\frac{X}{2\sqrt{T}}-\frac{\sqrt{T}}{2}\right)\right\}$$
$$+\left(\frac{c_i}{c_0}+\gamma^* X\right) \tag{24}$$

4. Dispersion along Inhomogeneous Aquifer: Numerical Approach

In a heterogeneous aquifer, permeability, dispersion coefficient as well as groundwater velocity vary with position, i.e., all are spatially dependent. The dispersion coefficient D and groundwater velocity u can be defined as

$$D=D(t)F(x) \qquad and \qquad u=u(t)F(x) \tag{25}$$

The partial differential equation (1) can be written as

$$\frac{\partial c}{\partial t}=F(x)\left[D\frac{\partial^2 c}{\partial x^2}-u\frac{\partial c}{\partial x}\right]+\frac{d}{dx}F(x)\left[D\frac{\partial c}{\partial x}-uc\right]+\gamma \tag{26}$$

Using non-dimensional variables defined in equation (14), equation (26) becomes

$$\frac{\partial C}{\partial T}=F(X)\left[\frac{\partial^2 C}{\partial X^2}-\frac{\partial C}{\partial X}\right]+\frac{d}{dX}F(X)\left[\frac{\partial C}{\partial X}-C\right]+\gamma^* \tag{27}$$

Function $F(X)$ is defined by two expressions (Kumar and Kumar, 1998):

$$F(X)=1-\frac{0.5\exp(-X)}{1.5+\exp(-X)} \tag{28}$$

$$F(X)=0.8-\frac{0.05\exp(-X)}{1.25-\exp(-X)} \tag{29}$$

in which the first expression increases from 0.8 at $X=0$ to 1.0 as $X\to\infty$ while the second expression has the reverse tendency. To find the numerical solution, two level explicit finite difference schemes are used. In order to convert the semi-infinite domain, $X\in(0,\infty)$ into a finite domain $Y\in(0,1)$, the following transformation is used

$$Y=1-\exp(-X) \tag{30}$$

Using the above transformation, equation (27) becomes

$$\frac{\partial C}{\partial T}=(1-Y)\left[F(Y)\left\{(1-Y)\frac{\partial^2 C}{\partial Y^2}-2\frac{\partial C}{\partial Y}\right\}\right]+\frac{d}{dY}F(Y)\left[(1-Y)\frac{\partial C}{\partial Y}-C\right]+\gamma^* \quad (31)$$

where $$F(Y)=1-\frac{0.5(1-Y)}{2.5-Y} \quad (32)$$

and $$F(Y)=0.8-\frac{0.05(1-Y)}{0.25+Y} \quad (33)$$

Now $F(Y)$ has the same variation in $Y\in(0,1)$ as does $F(X)$ in domain $X\in(0,\infty)$. Converting the initial and boundary conditions in equations (2) to (4) in the Y domain, they become

$$C(Y,T)=\frac{c_i}{c_0}+\gamma\log\frac{1}{1-Y},\ Y>0\ ,T=0 \quad (34)$$

$$C(Y,T)=\frac{1}{2}\left[1+\frac{QT}{2}\right],\qquad Y=0\ ,\ \ T>0, \quad (35)$$

$$\frac{\partial C}{\partial Y}=0\ ,Y=1\ ,T>0 \quad (36)$$

As $Y=1$ corresponds to $X\to\infty$, i.e., $x\to\infty$, it is not possible to get concentration values at infinity. Therefore, the values are evaluated up to some finite extent along the longitudinal direction, away from the origin with the implicit assumption that the upper boundary is placed far enough upstream for the concentration (due to zero order production term) to remain unchanged with time. Let the values be computed up to $x=l$, which corresponds to $Y=1-\exp(-(u_0 l/D_0))=Y_0$ in domain $(0,1)$. Also the analytical solution makes it clear why the concentration gradient at $x\to\infty$ is considered finite, instead of as usual, being taken as zero in the second boundary condition, although condition $\frac{\partial c}{\partial x}=0\ ,x\to\infty\ ,t>0$ will also yield the same analytical solution as obtained here.

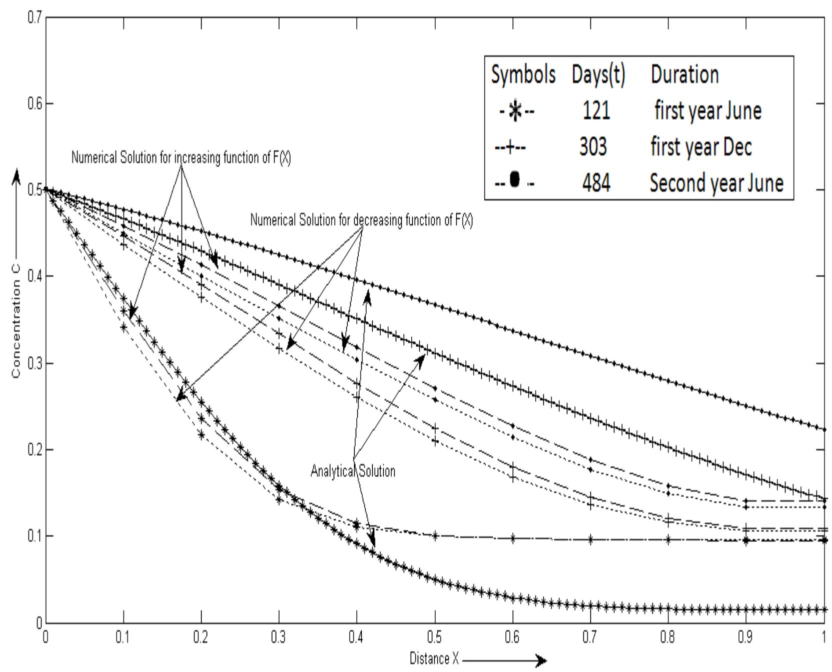
5. Numerical Results and Discussion

For the given problem, two forms of unsteady groundwater velocity are considered (Banks and Jerasate 1962; Kumar 1983).

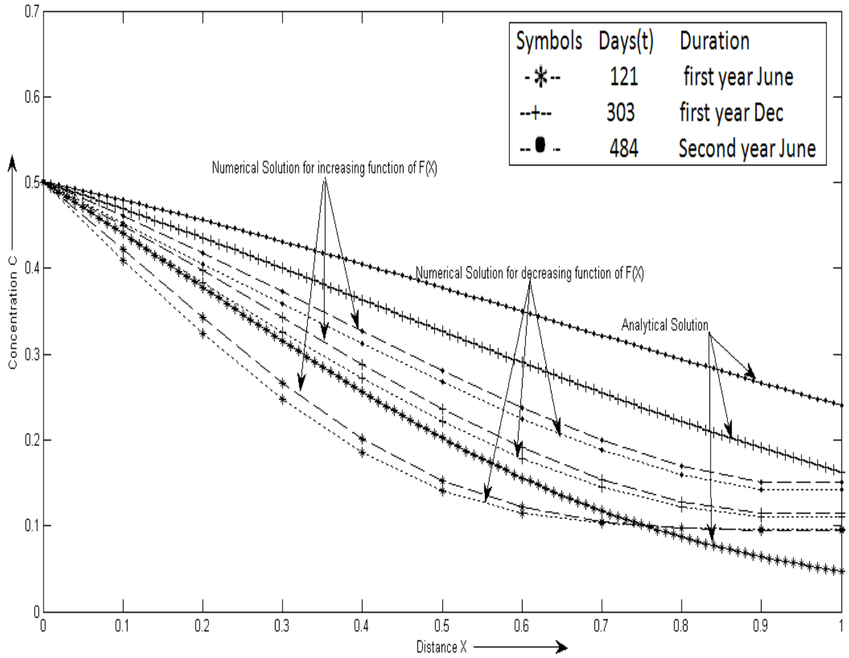
$$u(t)=u_0(1-\sin mt) \quad (37)$$

$$u(t)=u_0\exp(-mt), mt<1 \quad (38)$$

The analytical and numerical solutions (for both increasing and decreasing functions $F(X)$ as given in equations (28) and (29), respectively, are computed for input values considered as: $u_0=0.01$km/year , $D_0=0.1$ km^2/year , $\gamma_0=0.5\times10^{-5}$km^{-3}/year , $c_0=1.0$, $c_i=0.01$, and $q=0.00001$(/ year). The flow resistance coefficient m is chosen as 0.0165(/year). The value of mt is chosen as $3k+2$, where k is whole number and in particular, $0\le k\le 2$ is taken in the present discussion. Here $u(t)$, expressed by equation (37), is minimum and maximum alternatively for these values of mt which means that the velocity has this kind of tendency at $t=(182k+121)$ days, where k is the whole number at a regular interval of 182days. Let $t=121$ days correspond to some day in the month of June during which the groundwater level and the velocity is minimum; this period is the peak of summer season just before rainy season. Then, next value $t = 303$ days corresponds to approximately the same day in the month of December, the peak of winter season, just after the rainy season, during which the groundwater level and velocity are maximum. Further, the next value $t = 484.8$ days will correspond to almost the same date in the month of June in the next year and so on. Fig. 1a shows the concentration distribution for the sinusoidal form of velocity. It is observed that the source concentration decreases with distance and increases with time. The decreasing tendency of the contaminant concentration is faster in time $t = 121$ days and the same will continue for further time intervals. The numerical solution obtained for the heterogeneous aquifer is compared with the analytical solution obtained for the homogeneous aquifer, in which it is shown that the concentration distributions for both the solutions are approximately the same. Also, there are no changes in the pattern of concentration distribution obtained by the numerical method for different functions, $F(X)$. Fig. 1b depicts the concentration behavior for an exponentially decreasing form of velocity. It also shows the decreasing tendency of contaminant concentration, which reaches the minimum or harmless concentration for $m = 0.0002(/\,year)$, $mt < 1$, is the same as for the sinusoidal velocity for $m = 0.0165(/\,year)$. The analytical and numerical solutions are also compared for the exponential form of velocity. In the present discussion, the analytical solution for the homogeneous aquifer and the numerical solution for increasing as well as decreasing nature of heterogeneity are explored and represented in Figs.1(a, b). These representations are made for sinusoidal as well as exponentially decreasing forms of flow velocity through which contaminant concentration is predicted.



a



b

Fig. 1 Concentration distribution pattern with time dependent input along a) sinusoidally varying and b) exponentially varying unsteady velocity for both homogeneous and heterogeneous aquifer.

6. Conclusions

An analytical solution is obtained for a homogeneous aquifer and a numerical solution is obtained for increasing and decreasing nature of heterogeneous aquifer. Both the solutions have identical nature of contaminant distribution behavior. The following conclusion can be made:

(i) Analytical solution of an advection-dispersion equation for non reactive solute transport is able to describe the contaminant distribution pattern in homogeneous aquifer subjected to suitable initial and boundary conditions. This helps to benchmark the numerical codes and solution.

(ii) Analytical solution for heterogeneous aquifer is quiet complex and so it is difficult to obtain closed form solution. Numerical solution is applicable to describe the contaminant distribution pattern in heterogeneous aquifer though it provides approximate solution which is nearly closed to analytical one.

(iii) The contaminant concentration distribution patterns are depicted with position for first two year of prediction in June and December of every year. The result may be used as a preliminary predictive tool in groundwater resource management.

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