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Development of Hydrological Model for Sustainable Irrigated Agriculture in Al-Ahsa Oasis

[1]Ahmed A. Al-Naeem, [2]Parvaiz A. Cheema and [3]Ghulam Hussain
[1]Department of Soil and Environment, College of Agriculture and Food Sciences, King Faisal University, P.O. Box 380, Hofuf, Al-Ahsa, 11982, Kingdom of Saudi Arabia
[2]Former Civil Engineer, HIDA, Hofuf, Al-Ahsa, Saudi Arabia
[3]National Center for Water Technology (NCWT), KACST, P.O. Box 6086, Riyadh, 11442, Kingdom of Saudi Arabia

Abstract: One of the major problem of arid regions is inadequate irrigation supplies to sustainable irrigated agriculture. Al-Ahsa oasis is one of the largest irrigated agriculture areas in Saudi Arabia. Presently, urban and rural expansion have caused serious impact on the existing water resources which resulted in poor land productivity. The main objective of this study was to develop a hydrological model for sustainable irrigated agriculture in Al-Ahsa Oasis considering the climate, spring discharge, spring water level, main water aquifers and their water level, drainage discharge, potential evaporation, precipitation, crop water requirements and urban water use in the Oasis. Regression equations were used to develop hydrological model. The results showed that the extraction of groundwater from Neogene aquifer affects the spring levels more than the extraction from Alat or Al-Khobar aquifer. The regression analysis indicated a strong interaction between the aquifers. The Alat and Al-Khobar aquifers were found closely interconnected. The study provided a guidance to the policy makers to decide the extent of water extraction from the Neogene aquifer. A significant decline was observed in the water level of springs. The study highlighted more pumping of groundwater by digging new wells to replace spring discharge for water supply to meet the growing water needs of agriculture sector. In conclusion, the study results can help Hassa Irrigation and Drainage Authority (HIDA) for long-term planning of water resources to maintain at least the existence agricultural productivity of Al-Ahsa oasis.

Key words: Hassa irrigation and drainage authority, aquifers, spring water level, crop water requirements, climate, hydrological model, water extraction

INTRODUCTION

One of the most serious problem facing the arid regions around the world is efficient utilization of limited water resources. The environmental factors such as high air-temperature, low rainfall, high water potential evaporation rates, inadequate irrigation supplies and aridity have serious impact on agriculture productivity. Other major problems of arid regions are limited and non-renewable groundwater resources, injudicious use of the available water supplies and improper distribution of water resources among the farming community for optimal crop production. Recently, Kannan *et al*. (2011) developed an approach to model canal irrigation systems and irrigation best management practices (BMPs) to adequately simulate the water balance of irrigated watersheds. They considered water requirement of crops, number and frequency of irrigation and critical crop water requirement stages during the study. While, Cai *et al*. (2003) stated that interdisciplinary nature of water resources problems requires the integration of technical, economic, environmental, social and legal aspects into a coherent analytical framework. They developed an integrated hydrologicagronomic-economic model in the context of a river basin where irrigation was the dominant water user. Martin (2005) reported that in the Atankwidi catchment, West Africa, the annual precipitation is around 990 mm distributed over rainy (April to October) and dry (October to March) seasons. The annual mean temperatures are above 18°C and monthly rainfall exceeds potential evaporation for 2-7 months per year. Bharati *et al*. (2008) evaluated the conjunctive use of surface and groundwater in small reservoir-based irrigation systems characteristic of the Volta Basin, Africa by applying a dynamically coupled economic-hydrologic simulation-optimization model. The study results included

Corresponding Author: Ahmed A. Al-Naeem, Department of Soil and Environment, College of Agriculture and Food Sciences, King Faisal University, P.O. Box 380, Hofuf, Al-Ahsa, 11982, Kingdom of Saudi Arabia

the optimal water storage and allocation regimes for irrigated production, given conjunctive surface water and groundwater systems.

Bastiaanssen *et al.* (2005) concluded that water management emphasis tends to shift from supply augmentation to limiting water consumption. They further stated that spatio-temporal information on actual Evapo-transpiration (ET) helps users to better understand evaporative depletion and to establish links between land use, water allocation and water use. Also, for a range of soil wetness and plant community conditions, the typical accuracy at field scale was 85% for 1 day and it increased to 95% on a seasonal basis. The accuracy of annual ET of large watersheds was found to be 96% on the average. Leavesley *et al.* (2002) suggested a modular approach to model design and construction which provided a flexible framework to focus the multidisciplinary research and operational efforts needed to facilitate the development, selection and application of the most robust distributed modelling methods. The US Geological Survey Modular Modelling System (MMS) is a modular modelling framework that uses an open source software approach to enable all members of the scientific community to address collaboratively the many complex issues associated with the design, development and application of distributed hydrological and environmental models. Refsgaard and Abbott (1996) reported that scarcity and misuse of fresh water pose a serious and growing threat to sustainable development and protection of the environment. Human health and welfare, food security, industrial development and the ecosystems on which they depend, are all at risk, unless water and land resources are managed more effectively in the present situation. Kite (2000) used distributed hydrological model to compute daily evaporation and transpiration for a variety of crops and other land covers within the 17,200 km^2 Gediz Basin in western Turkey. The model, SLURP, described the complete hydrological cycle for each land cover within a series of sub-basins including all dams, reservoirs, regulators and irrigation schemes in the basin. The results showed that evaporation and transpiration vary widely across the basin on any one day and over the irrigation season and can be used to evaluate the effectiveness of the various irrigation strategies used in the basin.

Agriculture is considered the main user of water exceeding more than 80% around the world. However, to implement a viable water use policy, it is important to know the available water resources and the various functions of the existing hydrological system. Presently, one of the most useful technology is to develop mathematical and simulation models of the existing hydrological system. Todd (1980) concluded that simulation modeling of a hydrological system is standard practice to optimize water resources utilization. Previously, some investigators reported simulation of hydrological systems such as rainfall-runoff models (Linsley *et al.*, 1968), stream flow stochastic models (Yevdevich, 1974) and water use models considering both the crop demand and domestic uses (Helweg, 1984). Besides, traditional statistical analysis includes data collection, management, manipulation, interpretation, application in water resources management for agriculture production with minimal use of water resources (Mendenhall and Scheaffer, 1973).

The main objective of this study was to develop a hydrological model for sustainable irrigated agriculture in Al-Ahsa oasis considering all the main factors of the Al-Ahsa Oasis such as groundwater hydrology, irrigation system, drainage system, potential water evaporation, rainfall and crop water use.

DESCRIPTION OF STUDY AREA

Location: Al-Ahsa often referred to as the largest and the oldest Oasis in the Arabian Peninsula is located in the Eastern Region of Saudi Arabia about 150 km south of the port of Dammam and 320 km south-east of Capital city Riyadh. It extends from around 25°21' to 25°37' North and from 49°33' to 49°46' east. It embraces an L-shaped area of 320 km^2 with vertical stroke lying in a due north-south direction and the provincial capital Hofuf lying in the corner of the L. The entire cultivated area, which used to be around 20,000 ha, does not exist as today due to expansion around the towns of Hofuf and Mubaraz in the south-western corner of the Oasis. However, the overall area is considered as twin Oases with one Oasis in the north and the other Oasis in the south as shown in Fig. 1.

Area: Al-Ahsa districts is about 25 km long from north to south and 15 km wide from east to west at its southern end point. The eastern Oasis consists off the main block of cultivation and is the largest in area and most densely populated. It has an east-west axis of some 26 km and a north-south distance at its widest point (around 26 km east of Hofuf) of about 10 km. The northern axis is about 17 km in length along its north-south axis and a maximum east-west width of some 6 km. Both these oases together form the largest oasis districts of Kingdom of Saudi Arabia. The total cultivated land used to be 20,000 ha which has decreased due to many factors namely poor drainage system, sand dunes encroachment of agriculture area and inefficient irrigation practices coupled with inadequate drainage resulted in water logging and high salt concentration in large area of the oasis.

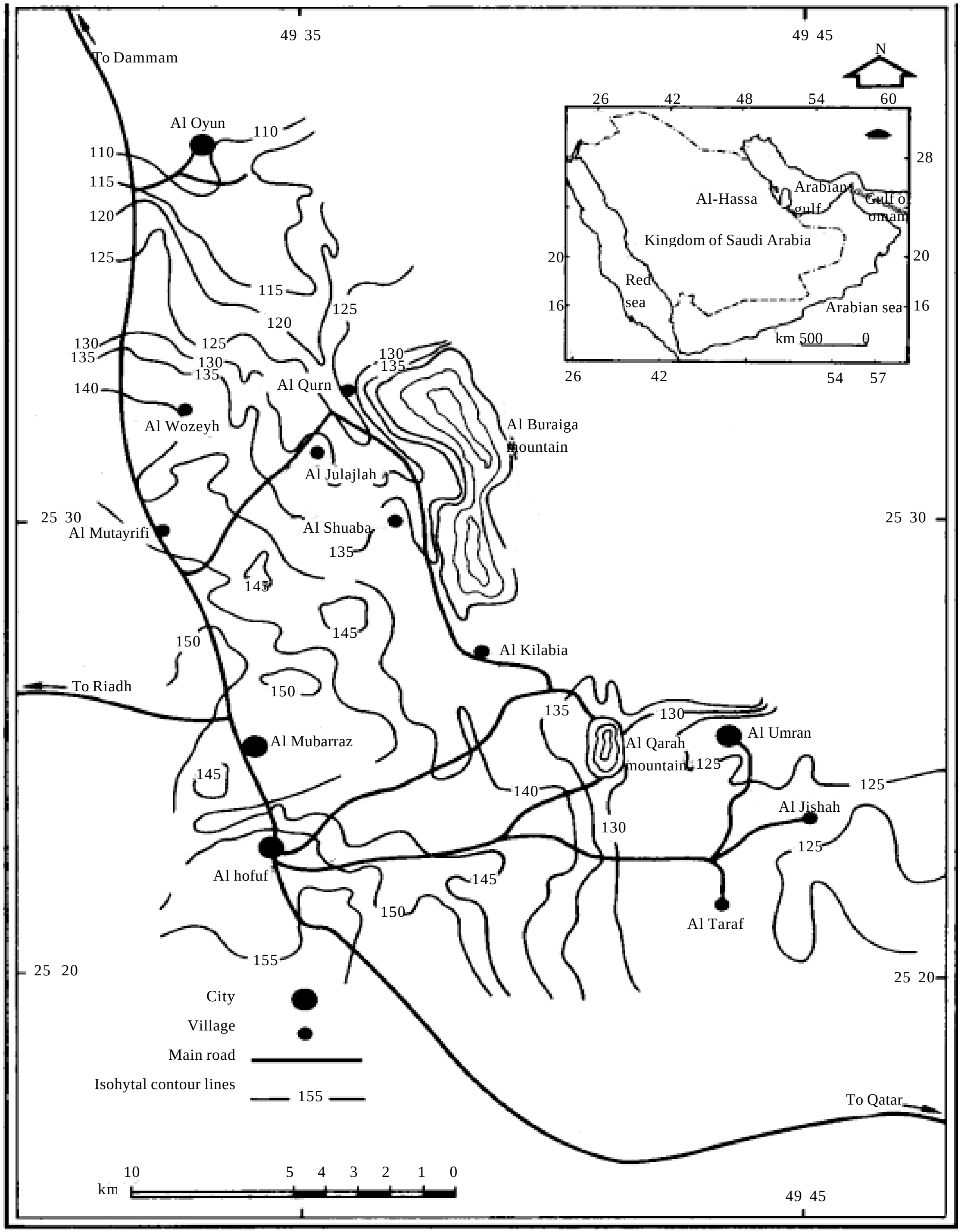

Fig. 1: Location Map of Al-Ahsa Oasis

According to Vidal (1951), the maximum area under cultivation was 16000 ha which was then reduced to 10400 ha as assessed by Wakuti Consultant Engineers in 1963-64 (Wakuti Consulting Engineers, 1964, 1969). Till the late 1960's, almost 12,000 ha arable land was lost and the total cultivated area was just over 8,000 ha. However, after the construction of Irrigation and Drainage Project of Al-Hssa from 1967-1971, the authority made an effort to reclaim more and more area and as such the total area under cultivation came to over 11,500 ha in 1983 according to HIDA's Statistical Section (HIDA, 1984).

Topography: The oasis is bordered in the East by a chain of hills (Jabal Buraiga). However, in the Oasis there exists icebergs typical for eroded areas, the highest being the Jabal Qarah situated at the northern border of the Eastern Oasis. The elevation of these hills reaches about 230 m above sea level (Fig. 1).

WATER RESOURCES

Three aquifers namely Neogene, Dammam and Umm er Radhuma are the main source of ground water in Al-Hassa Oasis. The water quality varies within each aquifer as well as between different aquifers. Currently, all the water needs such as irrigation, domestic and industrial water are fulfilled from groundwater of the Neogene aquifer in the whole Oasis. According to an estimate, agriculture sector consumption accounts for more than 80% of the total water use in the Oasis. The depth of Neogene aquifer (Miocene-Paleocene) ranges between 100 and 200 m as investigated by BRGM (1977). This aquifer consists mainly of conglomeratic sand, sandstone and heavily fissured limestone. Dammam aquifer underlies the Neogene aquifer is mainly dolomite and dolomitic limestone. Umm-er-Raduma aquifer (Paleocene-Eocene) underlies the Khobar aquifer and consists mainly of massive dolomite and dolomitic limestone.

Previously, springs were the main sources of irrigation water supply in Al-Ahsa Oasis, but the un-necessary groundwater extraction caused significant decline in the groundwater level of almost of the springs. Presently, there is no gravity flow of water from springs which has been replaced by the tube wells for pumping water to fill the irrigation canal system to meet water needs of the farming community. However, for information sake, monthly discharge from 32-springs is presented from 1974-1984 in Table 1. Besides, water level of springs recorded on monthly basis is presented from 1974-1983 in Table 2. The discharge from drainage canals is presented from 1974-1984 in Table 3.

Geological conditions: The Al-Ahsa Oasis is located on the central plain, a flat area north to south, fanning out from the north where it is only 8 km wide immediately north of Al-Uyun and becoming wider (35 km at Hofuf) as it proceeds towards south. This central plain is bordered on the east by the sands of the Jafurah and on the west by the Summan scarp, the edge of the Summan Plateau. The oases are not on a uniform height within the central plain. The eastern oasis in located in a deep hollow which continues south-southwest of Hofuf fro upto 40 km. Geologically, the sediments of the area are Quartenary (Gravel and sand dunes), Neogene (conglomerates,

Table 1: Monthly discharge from 32 springs in million cubic meters from 1974-1984

Year/month	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	Mean
January	13.65	14.58	15.47	13.85	17.18	18.11	18.06	18.09	16.74	15.88	19.42	16.74
February	15.28	15.61	12.88	16.24	15.52	17.15	16.11	17.63	14.71	16.29	18.62	16.05
March	18.00	19.92	15.38	18.90	19.01	19.70	19.44	19.40	14.99	15.14	17.75	17.84
April	21.87	20.96	18.44	19.64	22.88	21.73	23.88	20.34	18.67	18.70	19.59	20.45
May	24.10	2223	23.74	24.87	22.65	21.06	23.20	21.88	22.95	20.43	19.23	22.07
June	21.34	2217	22.63	21.57	19.42	18.47	21.13	19.52	21.53	20.43	16.59	20.17
July	21.49	21.11	21.09	22.70	20.43	20.15	20.80	19.97	18.45	17.47	17.51	19.76
August	21.30	21.37	20.69	21.61	19.06	18.53	21.10	21.02	21.64	19.76	18.24	20.08
September	19.60	20.45	18.44	19.12	19.36	17.83	19.67	19.42	17.43	17.25	15.64	18.26
October	18.87	18.99	19.74	21.41	20.49	18.75	18.75	16.18	17.65	19.78	18.03	18.82
November	19.36	19.04	18.01	16.20	17.43	18.13	17.44	17.63	12.07	18.15	19.30	17.21
December	14.13	14.47	14.63	17.41	18.57	17.82	17.64	18.10	15.46	19.34	19.56	17.27

Source: HIDA (1984) (Water Research Department)

Table 2: Monthly average water level of springs in meters above mean sea level from 1974-1983

Year/month	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
January	143.60	143.45	143.38	143.20	143.10	142.97	143.10	142.96	142.96	142.92
February	143.90	143.80	143.77	143.50	143.25	143.00	142.79	142.83	143.39	143.08
March	143.80	143.70	143.86	143.50	143.00	142.64	142.24	142.50	143.00	142.99
April	143.40	143.30	143.17	142.80	142.40	142.15	141.89	142.06	142.46	142.42
May	142.45	142.40	142.29	142.00	141.90	141.79	141.69	141.69	141.89	141.66
June	141.85	141.80	141.72	141.70	141.80	141.97	141.89	141.76	141.90	141.68
July	141.85	141.90	141.70	141.60	141.90	142.20	142.00	141.72	141.64	141.58
August	141.82	141.82	141.77	141.70	142.00	142.07	142.89	141.76	141.74	142.59
September	142.50	142.48	142.36	142.30	142.20	142.23	142.29	142.16	142.02	141.24
October	142.75	142.70	142.57	142.50	142.30	142.34	142.45	142.27	142.89	142.22
November	142.95	142.90	142.74	142.70	142.60	142.61	142.75	142.49	143.23	142.60
December	143.55	143.50	143.45	143.20	143.00	142.86	142.87	142.89	143.45	143.15

Source: HIDA (1984) (Water Research Department)

Table 3: Monthly discharge through drainage canals in million cubic meters from 1974-1984

Year/month	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
January	15.74	15.48	14.24	24.13	19.62	11.28	17.58	14.73	13.66	14.85	13.46
February	16.06	15.93	16.68	15.39	15.42	10.87	21.99	12.70	13.80	12.63	12.12
March	16.58	13.77	19.18	13.76	15.30	11.76	14.20	12.86	16.90	14.83	12.19
April	13.30	12.20	13.49	10.79	13.02	9.02	12.56	10.08	12.46	13.23	10.23
May	10.47	9.39	9.38	9.06	10.98	8.07	8.44	7.13	8.29	9.23	7.39
June	6.12	5.17	5.21	5.86	6.17	3.91	3.37	4.10	6.13	4.09	4.92
July	5.09	4.11	4.72	3.57	5.49	2.86	3.03	2.97	3.92	3.90	4.05
August	4.79	3.82	4.42	3.76	3.56	2.90	2.61	3.19	3.75	4.66	4.48
September	5.78	4.61	4.15	3.40	5.64	4.38	4.66	3.97	4.46	4.76	5.42
October	6.57	4.66	5.39	5.86	7.51	7.24	7.65	5.71	5.63	6.58	7.52
November	8.23	8.01	8.34	8.76	9.46	7.42	8.27	6.69	9.97	9.94	9.87
December	12.83	10.00	10.22	14.20	17.10	12.24	10.91	10.93	12.96	11.98	12.27

Source: HIDA (1984) (Water Research Department)

Table 4: Yearly mean monthly air temperature (Unit: °C)

Month	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	Mean
January	16.3	14.2	14.6	13.0	12.7	14.1	14.1	13.9	11.6	15.1	15.9	14.1	15.8	14.1	13.7	14.2
February	15.6	18.0	15.8	13.5	18.2	14.8	16.7	14.3	15.3	17.0	18.7	16.8	16.5	14.2	14.8	16.0
March	25.2	20.4	20.7	19.4	21.0	20.6	19.7	17.4	21.8	20.7	20.6	19.8	20.7	17.9	17.0	20.2
April	25.4	26.2	24.2	24.5	26.2	25.8	24.5	24.7	25.0	27.2	25.9	26.6	25.3	24.7	23.6	25.3
May	30.3	30.7	30.8	28.7	30.7	29.7	31.4	30.8	30.9	34.3	30.1	29.0	31.1	30.3	30.7	30.6
June	33.1	33.0	31.2	33.4	32.6	32.6	34.8	34.6	34.5	35.2	35.5	33.3	32.6	33.5	33.3	33.6
July	33.6	34.4	34.5	34.1	34.2	33.2	34.9	34.4	36.6	36.2	34.6	34.8	34.0	33.5	34.4	34.5
August	34.0	33.0	33.7	33.6	34.4	32.8	34.2	33.2	35.0	34.7	33.8	33.3	33.6	33.8	33.9	33.8
September	31.1	30.2	30.6	31.1	31.8	30.8	32.3	31.2	32.6	31.2	32.1	30.5	30.9	31.9	29.6	31.2
October	27.6	26.0	25.2	26.8	26.4	25.7	25.6	27.6	28.3	26.6	27.3	26.8	26.5	27.6	23.4	26.5
November	20.1	21.8	20.6	20.9	19.0	21.4	20.6	20.0	20.5	22.3	21.7	22.8	21.6	17.5	21.0	20.8
December	17.7	16.1	14.4	13.4	15.3	15.9	15.5	15.2	18.5	17.3	15.1	14.8	17.3	13.3	15.9	15.7
Mean	25.8	25.3	24.7.	24.4	25.2	24.8	24.9	24.5	25.9	26.5	25.0	25.2	25.5	24.4	24.3	25.2

Source: Lin (1984)

sandstones, sandy lime-stones, marls and shales) and Eocene (marine, lime-stones, cherts and shales).

However, the characteristics horizon of the region is the Hofuf phase of the Neogene (Hofuf Formation), said to be Pliocene in age and consists of: (1): Series of marls, sandstones, sandy lime-stones and shales, (2): Sandstone conglomerate. The Hofuf beds rest on uncomfortably on the basal continental lime-stones of Miocene age. Practically, the lime-stones are exposed everywhere in the oasis.

Climate of Al-Ahsa Oasis: The Al-Ahsa oasis is situated approximately 75 km west of Arabian Gulf and has a typically continental climate. The daily and yearly fluctuations are high with temperatures ranging from -7 to 50°C, but the night frosts are rare. The humidity is very low in summer months especially in May, June, July and August. While in autumn and winter (starting in September), the relative humidity is quite high approaching a maximum of 100%. During the summer months, the level of potential evaporation is very high due to high temperature and low humidity, whereas in winter months it decreases with the fall in temperature and increase in humidity. Mean annual rainfall is less than 100 mm per annum in the area.

The Al-Ahsa area is endangered by the dues, the sand storms are very important. The sand storms mainly come in the months of March through August. Sand storms occur on days when the wind speed or velocity is very high. The sand storms are severe causing the sand dues to travel slowly forward and the large areas are covered by the blowing sand.

Air-temperature: Yearly mean monthly air-temperatures from 1969-1983 are presented in Table 4. This data was collected from Hofuf Agricultural Research Center (HARC) which is situated in the northern oasis on Dammam road near the village of Al-Mutairfi. The temperature fluctuates uniformly between 0 and 20°C during the months of December, January and February. In March and April, it increases to about 40°C and reaches maximum values in the 50's in July and August. The temperature again decline from September to November (Lin, 1984).

Class-A Pan Evaporation: Mean monthly evaporation from 1974-1983 in presented in Table 5 (Lin, 1984). These were collected from the Hofuf Agricultural Research Center (HARC) using standard Class-A evaporation pan. In addition to above, mean monthly evaporation from irrigated canals I presented in Table 6 (Lin, 1984).

Precipitation: Total monthly precipitation was also recorded at the Hofuf Agricultural Research Center

Table 5: Mean monthly evaporation in mm day^{-1} from 1974-1983

Year/month	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
January	3.9	3.9	3.87	3.81	4.54	4.11	3.23	4.68	4.88	4.31
February	5.6	5.6	4.10	5.38	5.01	6.43	5.28	5.85	6.46	5.88
March	8.0	8.0	4.70	8.42	7.96	7.37	7.84	7.79	5.46	6.36
April	9.7	9.7	7.25	10.22	9.24	10.74	12.90	10.08	7.88	9.08
May	12.8	12.8	12.05	11.88	12.59	11.35	12.67	13.68	11.63	12.40
June	15.4	15.4	15.49	14.99	14.89	17.02	16.29	13.83	15.95	15.67
July	16.2	16.2	15.03	16.14	12.44	14.27	14.26	12.77	12.74	15.15
August	13.2	13.2	12.45	11.83	14.39	12.11	14.04	11.0	13.19	11.92
September	11.2	11.2	11.12	10.73	10.38	9.51	8.70	10.45	9.65	9.45
October	8.0	8.0	10.48	7.63	6.71	7.71	8.13	6.85	7.34	7.66
November	5.8	5.8	7.03	5.71	5.45	4.83	4.39	6.39	4.98	5.31
December	4.0	4.0	4.37	4.52	4.25	3.61	3.75	3.70	4.18	3.82

(Source: Lin, 1984)

Table 6: Mean monthly evaporation form irrigation canal surface in million cubic meters (MCM) from 1974-1983

Year/month	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
January	0.145	0.145	0.142	0.142	0.169	0.153	0.120	0.174	0.181	0.160
February	0.188	0.188	0.142	0.180	0.168	0.216	0.177	0.196	0.217	0.197
March	0.297	0.297	0.750	0.313	0.206	0.273	0.291	0.289	0.202	0.236
April	0.349	0.459	0.269	0.367	0.332	0.386	0.464	0.362	0.263	0.326
May	0.460	0.460	0.448	0.441	0.468	0.422	0.471	0.508	0.430	0.460
June	0.553	0.553	0.557	0.539	0.535	0.612	0.585	0.497	0.573	0.563
July	0.602	0.602	0.558	0.606	0.462	0.530	0.530	0.474	0.473	0.563
August	0.490	0.490	0.463	0.439	0.534	0.450	0.521	0.409	0.490	0.443
September	0.403	0.403	0.400	0.386	0.373	0.342	0.313	0.376	0.317	0.340
October	0.297	0.297	0.389	0.283	0.249	0.286	0.302	0.254	0.273	0.285
November	0.209	0.209	0.253	0.205	0.199	0.174	0.163	0.230	0.179	0.190
December	0.149	0.149	0.162	0.168	0.158	0.134	0.139	0.137	0.155	0.142

(Source: Lin, 1984)

Table 7: Total monthly precipitation received over Al-Ahsa oasisin million cubic meters (MCM) from 1974-1983

Year/month	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
January	1.29	6.02	5.89	14.59	0.48	0.90	6.64	0.74	-	4.26
February	0.96	3.84	11.23	-	2.69	0.13	18.56	2.18	9.34	-
March	15.87	0.99	16.86	4.29	0.26	2.27	4.80	5.76	16.42	18.08
April	0.32	3.78	5.02	3.07	0.42	-	-	-	15.01	-
May	2.12	-	1.34	0.26	-	-	-	-	-	-
June	-	-	-	-	-	-	-	-	-	-
July	-	-	-	-	-	-	-	-	-	-
August	-	-	-	-	-	-	-	-	-	-
September	-	-	-	-	-	-	-	-	-	-
October	-	-	3.04	0.77	-	-	-	-	3.42	-
November	-	-	-	0.09	0.54	-	-	-	10.69	-

(Source: Lin, 1984)

(HARC) and the data for the last ten years (1974-1983) is presented in Table 7 (Lin, 1984).

HYDROLOGY AND WATER SYSTEM

Important Aquifers: Important aquifers in the Eastern Region of Saudi Arabia are Wasia, Umm-Er-Radhuma, Al-Khobar, Alat and Neogene. These formation and depths are given in Fig. 2. As is evident from the Litho-stratigraphic section, Neogene, Alat and Al-Khobar are the important local aquifers which mainly supply water to the Al-Ahsa area through natural springs and wells. However, Neogene is the most important aquifer which supplies water to all the springs connected to HIDA network (Presently, the springs are out of production due to decline in water level and replaced by tube wells). Some observation wells were drilled at three locations around the oasis to monitor ground water level fluctuations. The mean annual water level from 1968-2012 is presented in Table 8.

Agricultural importance: Al-Ahsa is the largest agricultural unit in Saudi Arabia. Irrigated agriculture has been the main occupation of the inhabitants of the area for centuries since the land was irrigated from the water of the nearby flowing springs. But presently, the free flowing springs do not exist due to the decline in the water table and has been replaced by the tube wells for extraction of water from Neogene and Al-Khobar aquifers to meet crop water requirements. As such, the water level continuously

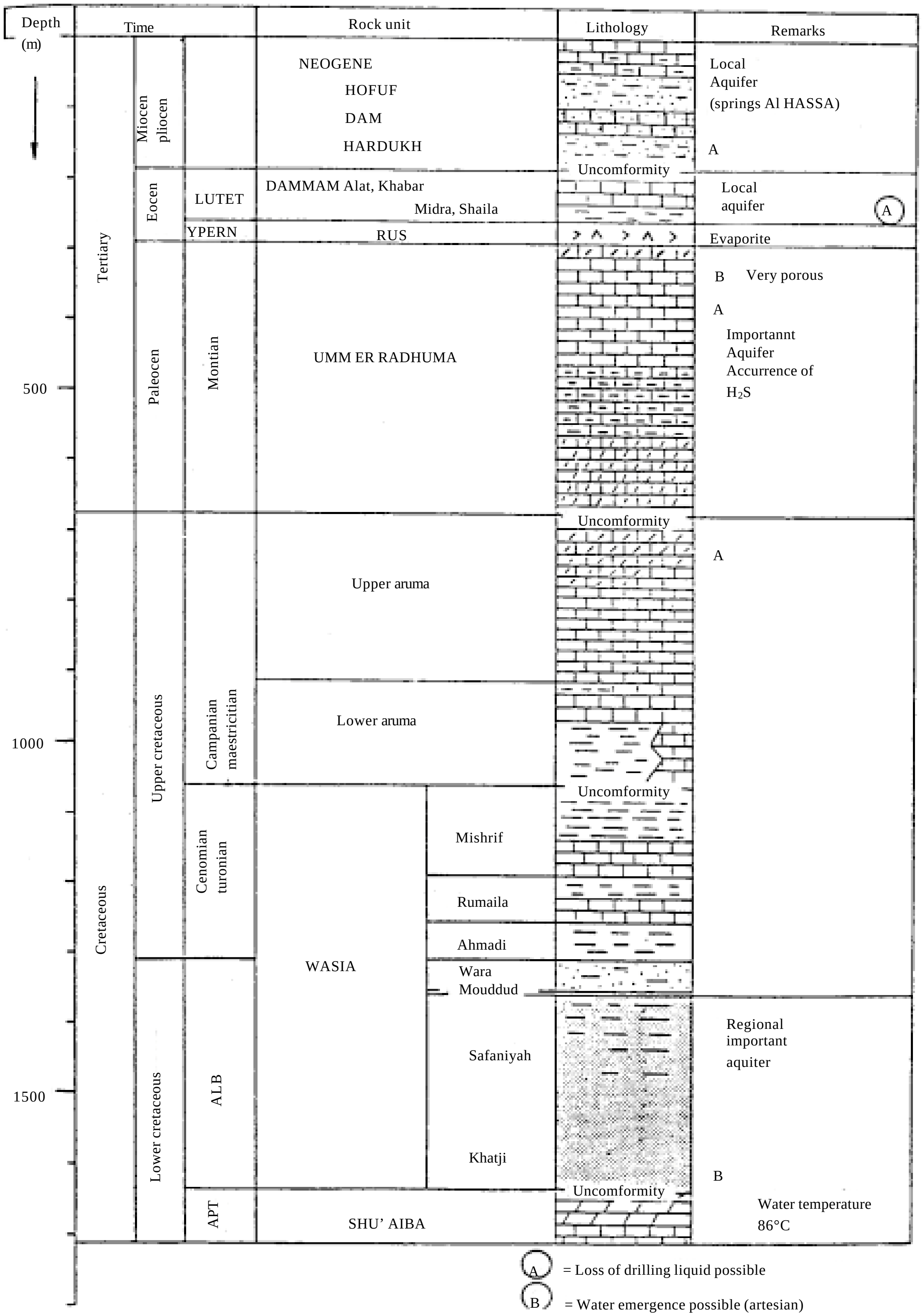

Fig. 2: Litho-stratigraphic section of Al-Ahsa Oasis

Table 8: Mean annual groundwater levels of Neogene, Alat and Al-Khobar Aquifers in Al-Ahsa Oasis (1968-2012)

Year	Neogene	Alat	Al-Khobar
1969	4.82	4.80	13.75
1970	9.09	4.60	13.52
1971	8.48	4.90	13.38
1972	8.46	5.15	13.77
1973	8.75	5.20	10.83
1974	8.79	5.30	11.31
1975	8.75	6.05	11.78
1976	8.68	7.20	12.44
1977	28.98	30.60	19.15
1978	28.87	33.27	20.06
1979	28.93	31.75	23.72
1980	28.75	32.19	24.72
1981	29.16	33.31	31.76
1982	29.11	36.15	37.67
1983	29.28	40.35	47.21
1984	29.89	44.69	65.55
1985	30.16	49.42	65.55
1986	30.37	50.48	69.43
1987	18.67	72.90	81.96
1988	31.16	57.90	78.69
1989	31.70	61.95	81.81
1990	32.27	65.06	83.53
1991	32.57	64.94	84.54
1992	33.13	63.28	85.79
1993	33.47	63.96	86.40
1994	35.70	65.80	89.78
1995	37.19	66.57	90.93
1996	36.94	65.72	90.90
1997	40.16	67.45	96.88
1998	41.51	68.77	100.38
1999	44.51	70.43	103.89
2000	46.33	72.43	107.31
2001	48.89	75.97	109.77
2002	47.93	76.97	111.24
2003	50.08	79.45	114.52
2004	50.34	80.50	119.32
2005	48.22	80.87	119.60
2006	48.39	82.74	121.19
2007	48.11	82.54	121.36
2008	48.91	84.37	121.29
2009	50.10	86.32	123.84
2010	51.90	88.39	125.32
2011	53.22	90.24	128.42
2012	54.04	92.33	128.33

declined and problems of water shortage started increasing resulting in loss of crop productivity of the arable land.

Total cultivated area: According to Vidal (1951), the total cultivated area was 16,000 ha which further reduced to 10,400 ha in 1963-64. Out of this, 2400 ha was not sufficient because of poor yields due to soil salinization. Only 8,000 ha produced sufficient yields. Main agricultural products of Al-Ahsa are alfalfa, dates, rice, vegetables, melons, pomegranate, lemon etc. According to the statistical report of the area by HIDA (1979-1980), the agricultural production was:

Total area of Oasis = 15,902 ha

Land able to be irrigated = 13,434 ha

Land actually cultivated = 7,096 ha

Fallow land = 6,338 ha

The major crops grown in the area (hectare) include alfalfa (1259), rice (152), wheat (33), onions (96), corn (3), vegetables (996), date palms and other fruits (4046). However, with the introduction of modern agricultural technology and adoption of new crop management practices, based on HIDA farmer's advisory services. The cultivated area increased according to statistical survey in 1983 by HIDA which was found as alfalfa (1290), rice (1522), wheat (96), onions (99), corn (14), vegetables (96), date palms and other fruits (5844).

With above area in mind, the consumptive use was obtained for different crops to estimate the total consumptive use of water from 1974-1983 (Table 9).

Purpose and theory of hydrologic model

Purpose of model: The purpose of the hydrologic model is two-fold. First, it is kind of book keeping tool in which the equation of hydrologic equilibrium is constructed (a mass balance equation) to test the adequacy of the data and determine the quantities of water entering and leaving the system through major sources and sinks. Second, the model serves as a predictive tool in that, if the correlations are sufficiently good, the continued decline of groundwater levels may be forecasted.

Theory of the model: The model, then consists of two parts, the equation of hydrologic equilibrium (mass-balance equation) and the correlation equations. The mass-balance equation is deceptively simple in that rarely are all the components data known; Therefore, the equation is used to refine the data and sometimes to supply the missing component.

The prediction models are linear or multiple linear correlation models constructed from the historic data. From these, causal relationships may be suggested and tested for significance. For example, which aquifers supply water to which springs may be suggested. Also the interaction between aquifers was partially verified by correlations.

Equation of hydrologic equilibrium: The basic equation is simply as:

$$I = o + \Delta S \quad (1)$$

where, I is the inflow, o is the outflow and ΔS is the change in storage. However, for Al-Ahsa Oasis system, Eq. 1 becomes:

$$Q_p+Q_{gw}+Q_{sp} = Q_{et}+Q_e+Q_d+Q_u+E \quad (2)$$

where, Q_p is the precipitation, Q_{gw} is groundwater extraction, Q_{sp} is the spring flow (pumped), Q_{et} is evapo-transpiration, Q_e is potential evaporation, Q_d is drainage water, Q_u is urban use and E is an error term. All the values were measured in million cubic meters (MCM).

Although the above model is static, but it can be made dynamic by adding a subscript for the time period such as months or years. In this case, one of the variables can be chosen as the dependent variable and the model used to predict its future value from the given values of independent variables. In simulation theory, there is a calibration phase called synthesis and a prediction phase, called analysis (Fig. 3). The calibration phase should, when possible, be broken into a calibration step and a verification step. This is called "splitting sampling". If the parameters derived from the calibration step can predict the historical results of the second half of the historical data, then the modeler may have some degree of confidence in the model.

In this study, the equation of hydrologic equilibrium does not have parameters to find as the most simulation models such as finite difference or simple regression analysis; consequently, the split sampling is inappropriate. Instead, the errors generated for each time period were analyzed to redefine the model.

Regression equations: The regression equations follow the classical "least squares" technique in which the squared difference between the historical results and the model were summarized. The generalized model was formulated as below:

$$Y = XB + e \quad (3)$$

where, Y is the vector of dependent variables, X is the matrix of independent variables, B is the matrix of coefficients and e is the errors. The Eq. 2 written in extendable form for two independent variables is:

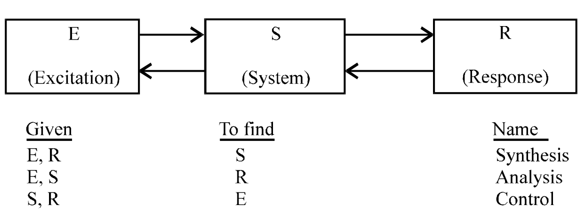

Fig. 3: Types of simulation

$$Y = B_o+B_1X_1+B_2X_2+e \quad (4)$$

If B is defined as the calculated coefficient vector (parameter vector), then it can be proved according to Leichtweiss-Institute Research Team (1978) that:

$$B = (X'X^{-1})\, X'\, Y \quad (5)$$

All the regression models follow this model. The matrix notation is merely another way of describing the standard normal equations, but it is more general.

Construction of model and calculations: The data for the mass balance model was entered in column files for statistical manipulation. Consequently, to utilize these data for the mass balance model (equation of equilibrium) the computer program was written to access files by following the procedure given in Statpack (1982) and Mendenhall and Scheaffer (1973).

The data for each term (Q value, Eq. 2) was entered into a separate file. These files were read into the program as needed. Basically, the program calculates the annual totals for each file since all data was entered as monthly values. After that, the equation of hydrologic equilibrium is solved for that year and the "error" or excess calculated and written to another file for later analysis.

An analysis of the input data indicates that the values for precipitation (Qp), spring discharge (Q_{sp}), drainage discharge (Q_d), evaporation (Q_e) from open bodies of water are fairly accurate, the later being rather insignificant. The uncertain terms were the groundwater discharge (W_{gw}), evapo-transpiration or consumptive use (Q_{et}) and urban use (Q_u). An additional uncertainty was about the amount of precipitation that evaporates before it filtrates into the soil or used by the vegetation.

The amount of precipitation (Qp) that was considered to enter the Al-Ahsa system was estimated at one fourth of the total precipitation. In semi-arid climates, as estimate of 10% of the precipitation is used to calculate the amount added to groundwater. Here the estimate is higher because of the sandy nature of most of the soil and rapid usage of vegetation.

The amount of groundwater that enters the system was estimated by taking the average decline of each major aquifer (Alt, Neogene and Al-Khobar) and multiplying it by the storativity and area under cultivated part of the Oasis. Storativity can only be estimated from a well test where an observation well is used, unfortunately, there were no available data to calculate this. Since the storativity of confined aquifers range from 0.00005 to 0.005, the limits of this value were variable. However, storativity can also be calculated from the following Equation.

$$S = 3\times10^{-6}\ b \quad (6)$$

where, b is the thickness of aquifer in meters. From the geological information available, S for all the aquifers was estimated to be 0.000012. Again, the irrigation efficiency was estimated to be 50%, so half of the pumped groundwater was considered to enter the system. The model outputs are presented in Table 10.

The urban use was calculated from empirical figure of 70 GPCD (gallons per capita per day). This is an established figure in the arid areas of Saudi Arabia, but there is no documentation of the genesis of the estimate. Another problem was obtaining the change of population in the area.

Construction of regression models: As stated above, the data for each value was entered into a separate file. For linear and multiple linear analysis, these files were combined, which was accomplished through a "zip" program (Mendenhall and Scheaffer, 1973). A new file was created from the separate files for each correlation based on the procedure of Leichtweiss Institute (1979). The correlation results gave the coefficients (parameters) as well as the coefficient of correlation and the "t" statistic for each independent variable. However, two main correlations were considered interesting, first: The correlations of the spring levels with other data such as groundwater levels, discharges and drainage. The second was to investigate any inter-correlation among the aquifers. The results of the spring level correlations and the inter-aquifer correlations are presented in Tables 11 and 12, respectively.

RESULTS (TRENDS, PREDICTIONS AND RECOMMENDATIONS)

Trends: The R-squared value multiply by 100 gives the percent of variation of the dependent variable that can be attributed to the variation in the independent variable. The following trends were observed:

Table 9: Total crop evapo-transpiration values in million cubic meters (MCM) from 1974-1983

Year/month	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
January	0.058	0.641	1.340	1.982	2.623	3.264	3.895	4.557	5.219	5.828
February	0.070	0.840	1.611	2.381	3.151	3.922	4.775	5.300	5.826	7.003
March	4.396	4.795	1.195	5.594	5.994	6.394	6.807	7.215	7.624	7.992
April	1.942	2.862	3.783	4.703	5.620	6.543	7.476	8.370	9.270	10.223
May	5.574	6.629	7.684	8.738	9.793	10.848	11.876	12.945	14.014	15.066
June	6.797	7.684	8.570	9.457	10.343	11.230	12.034	12.997	13.954	14.776
July	3.523	5.192	6.681	8.530	10.199	11.868	13.191	14.906	16.621	18.544
August	1.899	3.797	5.696	7.595	9.492	11.392	13.425	15.170	16.917	18.987
September	0.053	0.638	2.552	4.465	9.379	8.292	10.134	12.054	13.985	15.947
October	0.024	0.421	1.683	2.946	4.208	5.470	6.545	7.854	9.163	10.520
November	1.588	2.041	2.495	2.948	3.402	3.586	4.227	4.692	5.157	5.670
December	0.727	1.454	2.180	2.907	3.634	3.053	5.024	5.778	6.531	7.268

Table 10: Outputs of hydrologic balance model al-ahsa hydrologic equilibrium from 1974-1983 [No. in million cubic meters (MCM)]

Year	Precipitation (PRECIP)	Groundwater extraction	Flow from springs	Evapo-transpiration E.T.	Evaporation (EVAP)	Drainage flow	Urban use	Excess
1974	6.1	4.0	229.0	26.7	4.1	121.6	24.2	62.5
1975	4.9	6.8	228.9	37.0	4.1	107.1	24.2	68.2
1976	11.7	5.3	222.4	49.7	4.0	115.4	24.2	46.1
1977	5.9	8.1	233.5	62.2	4.1	118.5	24.2	38.5
1978	1.1	10.6	232.0	74.8	3.9	129.1	24.2	11.5
1979	0.9	15.6	227.4	86.1	4.0	89.9	24.2	39.6
1980	7.4	18.3	237.2	99.4	4.1	113.0	24.2	22.1
1981	2.2	34.6	229.2	111.8	3.9	95.0	24.2	30.9
1982	14.8	41.7	212.3	124.3	3.8	111.9	24.2	4.4
1983	5.6	47.2	217.9	137.8	3.9	110.8	24.2	-6.1

Table 11: Correlations with spring levels

Comparison	R-Squared value	Regression models
Spring levels vs Neogene GW levels	0.198	y = 129.90+0.01x
Spring levels vs Alat GW levels	0.089	y = 140.96+0.013x
Spring levels vs Al-Khobar GW levels	0.052	y = 141.09+0.012x
Spring levels vs Drainage flows	0.579	y = 141.56+0.103x
Spring levels vs Spring discharge	0.473	y = 145.80+0.173x
Spring levels vs Drainage and spring discharges	0.704	$y = 143.77+0.075x_1-0.103x_2$

Table 12: Correlations among aquifers

Comparison of water levels	R-squared value	Regression model
Neogene vs Al-Khobar	0.293	y = 123.40+0.14x
Alat vs Neogene	0.556	y = -374.08+3.55x
Alat vs Al-Khobar	0.911	y = -16.56+ 1.173x

- Pumping water from the Neogene, Alat and Al-Khobar aquifers did not show any significant effect on the spring level as indicated from low R-squared values which were 0.198, 0.089 and 0.052, respectively
- A fairly good correlation was found between the spring water level and the volume of drainage with a R-squared value of 0.58. This suggests that most of the drainage water is the result of spring irrigation
- A poor correlation was obtained between the discharge from springs (gravity plus pumpage) and the spring water levels with a R-squared value of 0.473. The poor relationship shows that spring are not naturally flowing but regulated from under ground aquifer
- There seems to be good correlation between the cumulative discharge from springs and the drainage canal to the spring levels (R-squared = 0.704)
- The percent of interconnection between Neogene and Alat, Alat and Al-Khobar and Neogene and Al-Khobar was 55, 91 and 29, respectively. A high correlation between the water levels of Alat and Al-Khobar (R-squared = 0.911) indicates that these two aquifers are strongly interconnected. Whereas, the interconnection between Alat and Neogene aquifers is very small (R-squared = 0.556)

Projections:

- Overall declining trend in the spring water levels was observed under the present land use and water management practices over a period of 10 years. Furthermore, the decreasing trend in the spring water level will be a continuous phenomenon if there is no significant change in the land use patterns in Al-Ahsa Oasis
- The water level of Neogene aquifer has dropped about 9 m from 1974-1983. Similarly, the water levels in Al-Khobar and Alat aquifers declined upto 35 and 48 m, respectively. Overall, there is a significant drop in the water levels of these aquifers

Recommendations:

- Monitoring of all the groundwater wells with respect to static and dynamic water levels, discharge and pumping efficiency should be properly handled in order to verify the result of the present investigation for efficient water management in the Oasis
- Crop consumptive of water should be determined scientifically under the local climatic conditions for efficient water use
- A comprehensive program should be developed to specify the quantity of irrigation water delivered to each farm
- Irrigation scheduling is required in Al-Aha oasis to improve water distribution efficiency

CONCLUSION

The developed hydrological model of Al-Ahsa Oasis can serve as a useful tool to determine the functions of hydrological system and its predicted long term effects on the current water exploitation. This will assist in providing a better understanding to the policy makers about Al-Aha Oasis with respect to water management. The hydrological model was developed for a period of 10-years from 1974-1983. The mass balance hydrological equation enumerates the inflows and outflows to the Al-Ahsa system. Also, the regression models indicated the effect on the spring level attributed to discharge from the springs, drainage flows and the groundwater extraction from different aquifers. The results showed that the extraction of groundwater from Neogene aquifer affects the spring levels more than the extraction from Alat or Al-Khobar aquifer. The regression analysis indicated a strong interaction between the aquifers and the degree of interaction. The Alat and Al-Khobar aquifers were found closely interconnected.

The study results provided a guidance to the policy makers to decide as to what extent water extraction from the Neogene aquifer should be controlled. A significant decline was observed in the water level of springs. It can be projected from the study results that after a period of time, either more pumping will be required, or well have to dug to replace spring discharge for water supply.

In conclusion, the study results can help HIDA for long-term planning of water resources to at least maintain the existence agricultural productivity of Al-Ahsa oasis.

REFERENCES

BRGM, 1977. Al-Ahsa development project groundwater resources study and management program. Report No. 77AGEO15, Final Report to Ministry of Agriculture and Water, Kingdom of Saudi Arabia.

Bastiaanssen, W.G.M., E.J.M. Noordman, H. Pelgrum, G. Davids, B.P. Thoreson and R. Allen, 2005. SEBAL model with remotely sensed data to improve water-resources management under actual field conditions. J. Irrigation Drain Eng., 131: 85-93.

Bharati, L., C. Rodgers, T. Erdenberger, M. Plotnikova, S. Shumilov, P. Vlek and N. Martin, 2008. Integration of economic and hydrologic models: Exploring conjunctive irrigation water use strategies in the Volta Basin. Agric. Water Manage., 95: 925-936.

Cai, X., D.C. McKinney and L.S. Lasdon, 2003. Integrated hydrologic-agronomic-economic model for river basin management. J. Water Resour. Plann. Manage., 129: 4-17.

HIDA, 1984. Annual report No. 23. Statistical Section, Water Resources Department, Hassa Irrigation and Drainage Authority, Hofuf, Saudi Arabia.

Helweg, O.J., 1984. Water Resources Planning and Management. John Wiley and Sons, New York, USA.

Kannan, N., J. Jeong and R. Srinivasan, 2011. Hydrologic modeling of a canal-irrigated agricultural watershed with irrigation best management practices: Case study. J. Hydrol. Eng., 16: 746-757.

Kite, G., 2000. Using a basin-scale hydrological model to estimate crop transpiration and soil evaporation. J. Hydrol., 229: 59-69.

Leavesley, G.H., S.L. Markstrom, P.J. Restrepo and R.J. Viger, 2002. A modular approach to addressing model design, scale and parameter estimation issues in distributed hydrological modelling. Hydrol. Process., 16: 173-187.

Leichtweiss Institute, 1979. The water potential of the Al-Hassa Oasis. LBID Publication No. 38, Leichtweise Institute, Saudi Arabia.

Leichtweiss-Institute Research Team, 1978. Water Resources of the Al-Hassa Oasis. Reports on the work of the Leichtweiss-Institute Research Team. Technical University Braunschweig. Al-Hofuf Agricultural Research Center. Al-Hassa. Saudi Arabia. Publication No. 22. Hofuf, 1978, pp: 43-44.

Lin, M.T., 1984. Agrometerology Study of Al-Hassa. OASIS, Al-Hofuf, Saudi Arabia.

Linsley, J., R. Kohler and H. Paulus, 1968. Water Resources Engineering. McGraw Hills, New York, USA.

Martin, N., 2005. Development of a water balance for the atankwidi catchment, West Africa: A case study of groundwater recharge in a semi-arid climate. Ph.D. Thesis, University of Gottingen, Germany.

Mendenhall, W. and R.L. Scheaffer, 1973. Mathematical Statistics with Applications. Duxbury Press, North Scieuate, USA.

Refsgaard, J.C. and M.B. Abbott, 1996. The role of distributed hydrological modelling in water resources management. Water Sci. Technol. Library, 22: 1-16.

Statpack, N.W.A., 1982. Northwest Analytical Laboratories. Portland Organization, USA.

Todd, D.K., 1980. Groundwater Hydrology. 2nd Edn., John Wiley and Sons, New York, ISBN-10: 047187616X.

Vidal, F.S., 1951. The oasis of Al-Ahsa; Final report. ARAMCO Local Government Relations, Arabian Research Division, Dhahran, Saudi Arabia.

Wakuti Consulting Engineers, 1964. Studies for project of improving irrigation and drainage in the region of Al-Ahsa. Vol. 4, Siegen, West Germany, Saudi Arabia.

Wakuti Consulting Engineers, 1969. Management study for Al-Ahsa irrigation and drainage system. Siegen, West Germany.

Yevdevich, V., 1974. Stochastic Hydrology. Water Resources Publication, Fort Collins, Co., USA.