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Estimation of Irrigation Demand Using GIS and Remote Sensing as Assisting Tools in River Nile State, Sudan

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ABSTRACT

The agriculture is the major consumer of fresh water. Most farmers are supplying more water than is crop required. In wide areas, remote sensing techniques may improve the estimates of water use since they provide global coverage, varied temporal and spatial resolution. The main objective of this study is to use satellite-based remote sensing (RS) data and geographic information system (GIS) as assistant tools for estimating crop water requirements and irrigation system demand for the large-scale areas. About 630,000 hectares to the Eastern South of Atbara River was chosen as study area. The metrological data were collected from six nearby metrological stations surrounding the study area. Satellite images were used to characterize soils and physiography supports by auger samples collected from each 25×25 Km2, as soil samples taken fromtwo depths 0-30 cm and 30-90 cm. All soil samples were tested and used for determination of various soil properties. CropWat software from FAO was used to estimate crop water requirements. Crop coefficients (Kc) for various major crops were estimated according to FAO recommendations. Three cropping patterns for the irrigated area were defined and discussed. The maximum water needs for the three options are almost the same. The maximum monthly water requirement is in August for the three options. The worst condition is 1012 million-m^3 $month^{-1}$ (1606 m^3 ha^{-1} $month^{-1}$). Thus, the discharge needs to satisfy the highest water demands is 33.7 mm^3 day^{-1} (53.5 m^3 ha^{-1} day^{-1}) in average of 14 working hours per day and the total discharge needed is about 670 m^3 s-1 (0.00106 m^3 ha^{-1} s^{-1}). Therefore, it is concluded that use of RS & GIS with CROPWAT software offers a reliable tool to estimate crop water requirements irrigation system demand for the large-scale area.

Keywords: Crop water requirements, Metrological data, Remote Sensing

تقدير احتياج الري باستخدام نظم المعلومات الجغرافية والاستشعار عن بعد كأدوات مساعدة بولاية نهر النيل - السودان

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مُسْتَخْلَص

الزراعة هي المستهلك الرئيسي للماء العذب، معظم المزارعون يقومون بتخزين الماء بقدر يزيد عن استهلاك الزرع. في معظم الأماكن من المحتمل أن تقوم تقنية الاستشعار عن بعد بتحسين تقدير كمية الماء المطلوبة حيث توفر التغطية العالمية، الترتيب الزمني المتعدد والتحديد المكاني. الهدف الرئيس لهذه الورقة هو استخدام بيانات الاستشعار عن بعد **(RS)**المستند على الأقمار الصناعية ونظام المعلومات الجغرافية **(GIS)**كأدوات مساعدة لتقدير احتياجات المحاصيل للماء ومطلوبات أنظمة ري المساحات الشاسعة. لهذه الدراسة، تم اختيار منطقة تقع جنوب شرق نهر عطبرة بمساحة 630,000 هكتار. تم تجميع بيانات الإرصاد الجوي من ست محطات للإرصاد الجوي محيطةبمنطقة الدراسة. استخدمت صور الأقمار الصناعية لتصنيف التربة وتموضعها وتم تدعيم ذلك بأخذ عينات بالحفر بالبريمة من كل 25 × 25 كم^2 ، حيث تم أخذ العينات من عمقين 0-30 سم و 30-90 سم. كل العينات أجريت عليها التجارب وتم تحديد خصائص التربة لها. تم استخدام برنامج الكروب-وات من منظمة الفاو لتقدير احتياجات المحاصيل للمياه. تم تقدير معامل المحاصيل لمختلف المحاصيل الرئيسية وفقاً لمتطلبات منظمة الفاو. تم تحديد ومناقشة ثلاثة أنماط للمساحة المروية. الاحتياج الأقصى للمياه للخيارات الثلاثة هو نفسه تقريباً. أسوأ حالة هي الاحتياجلـ 1012 مليون متر مكعب شهرياً (1606 م^{3}لكل هكتار في الشهر)وبالتالي، يحتاج التفريغ إلى تلبية أعلى طلبللمياه بمقدار 33.7 مم^{3}في اليوم (53.5 م^{3}لكل هكتار باليوم) بمتوسط 14 ساعة عمل باليوم والتفريغ الكلي يحتاج حوالي 670 م^3 في الثانية (0.00106 م^3 لكل هكتار بالثانية). وبذلك نخلص إلى أن استخدام**(RS)** و **(GIS)** مع برنامج الكروب-وات يوفر أداة ذات موثوقية مستخدمة لتقدير حاجة المحاصيل للمياه حسب مطلوبات أنظمة ري الأراضي الشاسعة

كلمات مفتاحية: متطلبات المحاصيل للمياه، بيانات الارصاد الجوي، الاستشعار عن بعد

Introduction

Irrigation is one of the most important inputs for efficient and sustainable agricultural production. On the other hand, irrigation water is limited and scarce in many areas of the world. Heermann and Solomon (2007) and Gontia and Tiwari (2010) stated that the agriculture sector is the major consumer of fresh water. Generally, farmers are supplying water more than crop requirement. Thus, better estimation of irrigation water demand is crucial for efficient water use, so water could be saved for future generations. The crop database on physiological characteristics of the crop and soil database as information on soil properties including texture, bulk density, water holding capacity, and soil depth are required for any calculation of water demand.

To achieve water conservation, Parmar and Gontia (2016) concluded the necessity that farmers should adopt new technologies for estimating crop consumptive use, more accurately crop evapotranspiration (ETc) to represents crop water requirement. Adamala *et al.* (2016) defined that a useful method to estimate crop water requirements is to multiplyreference evapotranspiration (ETo) by a crop coefficient (Kc) and this method can be done easily with the assistance of GIS and remote sensing techniques.

Romaguera *et al*. (2014) reported that remote sensing techniques may improve the estimates of water use since they provide global coverage, varied temporal and spatial resolution and broad information compared to traditional techniques that need large number of variables and parameters, requiring, in many cases, time consuming operations. Such methods allow characterizing the physical processes and monitoring crops in appropriate space and time scales. At the regional scale, other works, Bastiaanssen and Bos (1999) and D'Urso *et al.* (2012) used remote sensing to evaluate irrigation performance.

The *most* common methodologies for ET estimation from remotely sensed imagery are those based on vegetation indexes (VI) and soil water balance (SWB). That was suitable for cropped lands. However, for non-cropped lands other approaches may be more practical.

Bastiaanssen *et al.* (2005) and Reyes-Gonzalez *et al.* (2017) outline the Satellite-based remote sensing as an alternative to estimate crop water requirement and its spatial and temporal distribution on a field-by-field basis at a regional scale. These remote sensing based methods have been shown to be accurate. Muthanna and Amin (2003); Todorovic and Steduto (2003);

Suresh *et al.* (2012) concluded that utilization of geographic information systems (GIS) integrated with other special applications can be a solution for irrigation management.

This paper describes the use geographic information system (GIS) and, satellite-based remote sensing (RS) data compiled with terrestrial soil and meteorological inputs as assistant tools, for estimating irrigation demand for the large-scale area.

Materials and methods

The studied area (630000 ha) is located at the eastern border of River Nile State between 1,786,980-1,889,000 m North and 630,180-701,350 m East. About 102 kilometers length and 71 kilometers in width (Figure 1). The mean altitude is 387 m above sea level.

For the monthly climate parameters thirty years' measurements were collected from six nearby metrological stations surrounding the studied area, namely Atbara, Hudeiba, Shendi, New Halfa, Aroma and Derudeb (CLIMWAT2). ArcMap 9.3 and ArcView 3.1a were used to process the above climate data.

The Topography map of study area was derived from RS data (Digital Elevation Model SRTM90) using GIS program (Figure 2).

Hydrological data for Atbara River for the years 2002-2012 were collected from Egyptian irrigation office (Atbara).

The calculation of reference evapotranspiration (ETo) is based on the Food and Agriculture Organization (FAO) Penman-Monteith method (CropWat8). For the suggested crops the total periods, growth stages and planted dates, regional research recommendations were used. Crops coefficient, critical depilation, maximum rooting depths and yield response factors; FAO recommendations were considered.

Food and Agriculture Organization (FAO) CropWatprogram was used to design and management the irrigation scheme. Crop coefficients (Kc) for various major crops was estimated according to FAO methods.

Three croppingpatterns for the irrigated area were suggested. Monthly water requirements for the three cropping patterns were defined using CropWat8. Then the monthly water requirements were compared with monthly average yield for Atbara River.

Twelve quadratic working zones of studied area were identified from A-L (Figure 3). One hundred Auger samples were collected from each 25×25 Km Quadrate, soil samples were taken from two depths 0-30 cm and 30-90 cm. The distance between each auger holes was 2.5 kilometers along and between lines. Each auger hole was marked by GPS to be transferred to GIS maps.

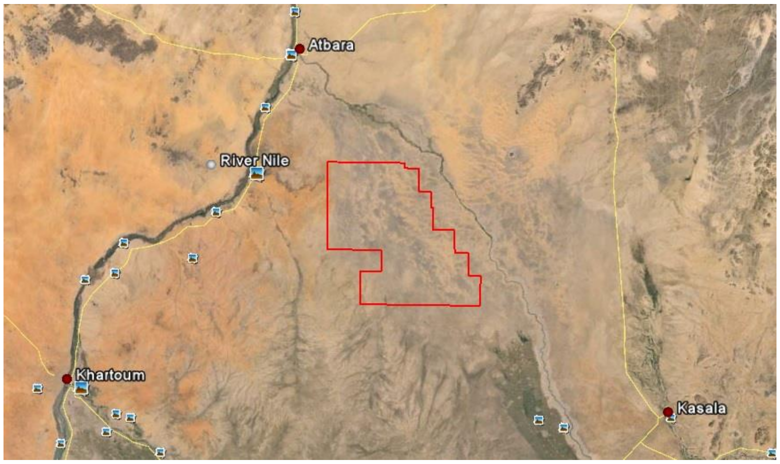


Figure 1. Spatial image of study area

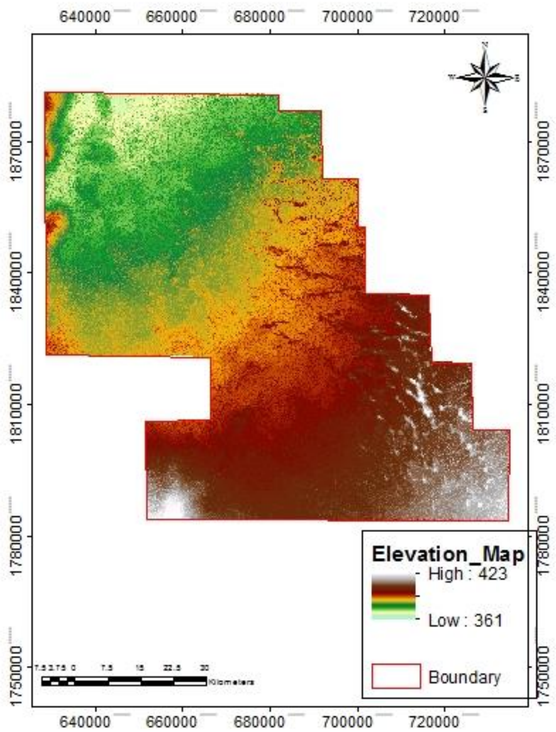


Figure 2. Topography map of studied area

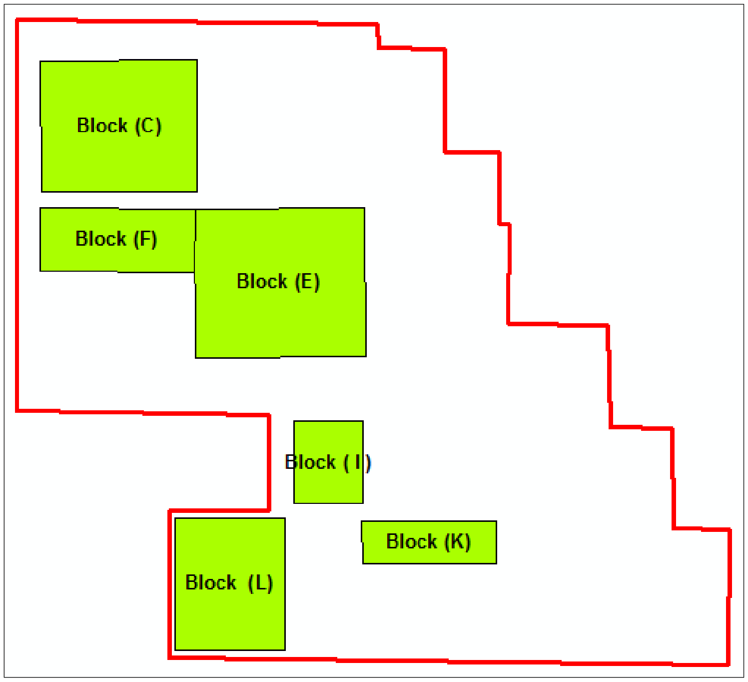


Figure 3. Quadratic working zones of studied area

The main crops that could be cultivated in the irrigated area was proposed due to consideration being given to irrigation possibilities, climatic limitations and land potential.

The digital elevation model (DEM) was further processed by Arc Map 9.3 to determine slopes of the studied area.

Results and discussion

The results of soil survey indicated that quadrate A, D, G, J and part of H were identified as sandy soils equal to 33% of the total area which was estimated as 630000 hectares. Differences in chemical properties detected between southern and northern parts like salinity and sodicity were distinguished as a factor of rainfall insufficiency and rainfall runoff towards low cantor areas.

Since soils in this area are of gentle sloping in the manner that can suit gravity irrigation. Set of limitations were used to categorize soil suitability including high sodicity range, high salinity range, shallow soil depth, problems of drainage, presence of large quantity of gravels, erosion hazards and fertility limitations.

The soil data were transferred to a geographical information system (GIS) and the distribution of sodicity and salinity were identified in maps Figures 4 and 5, respectively. The results of sodicity classes of top and subsoil indicated that 66 % of the studied area was nonsodic while 11 % was sodic. The distribution of salinity (Map Figure 5) characterized more than 60 % of the studied area in the range of 0 - 8 EC which can easily be leached to suit agricultural production. From spatial image of normal different soil colors darker areas represent vertisols and verticaridsols (clay soil) and light colors represent sandy soils. Field verification for deferent soil categories were then taken to determine the textural classes and other physical and chemical properties according to United States Department of Agriculture (USDA) procedures.

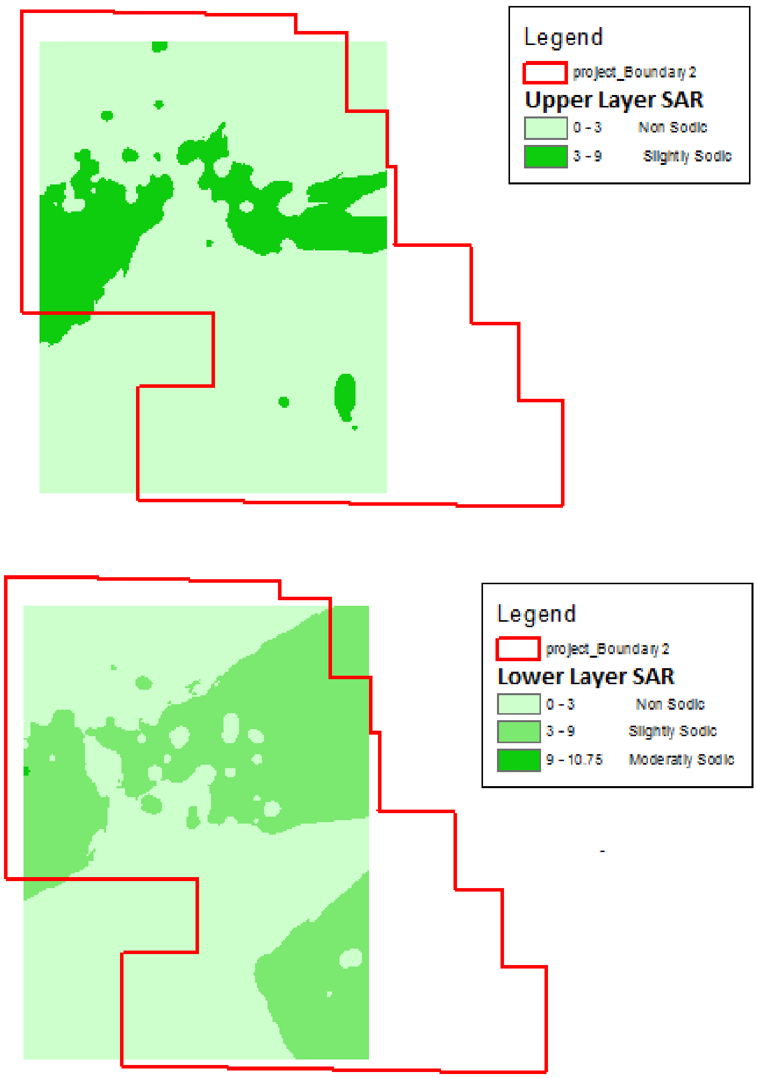


Figure 4. Sodicity classes of top and subsoil

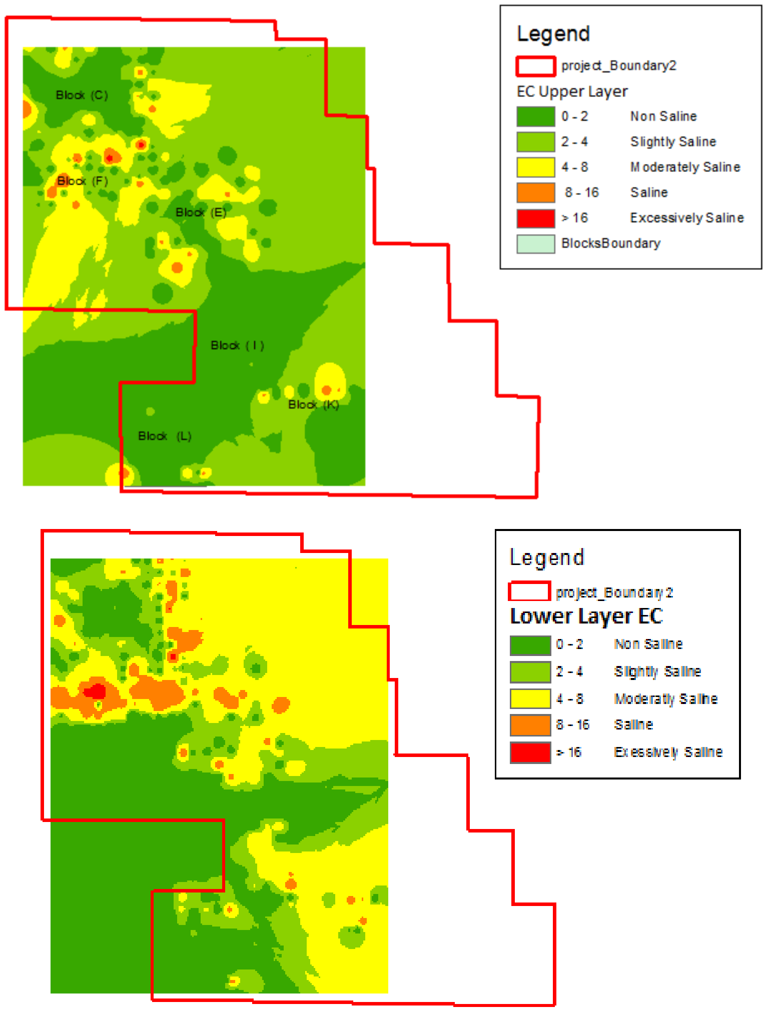


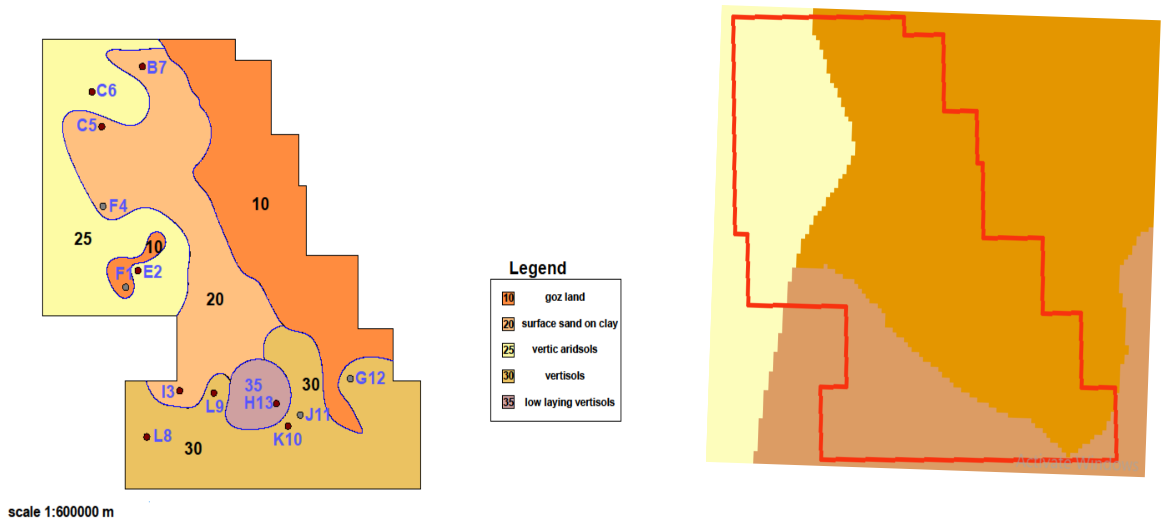
Figure 5. Salinity maps of top and subsoil

The texture of the soil according to United States Department of Agriculture (USDA) was classified and presented in Figure 6. According to the sutability classes for Agricultural production, most soils of the studied area with the exception of the Goz lands in Block A, D, and G could be classified in class II and III (Table 1).

Table 1. Area classification according to suitability for agricultural production

Area	%	Hectares	Remarks
Class II soils	66	415800	Nonsalinenonsodic leveled lands, poor in fertility and with low organic content
Class III soils	11	69300	With relatively high salinity and or sodicity leveled lands
Class VI soils	33	207900	Sandy Goz lands

Total	100	630000



*** USDA suitability classification**

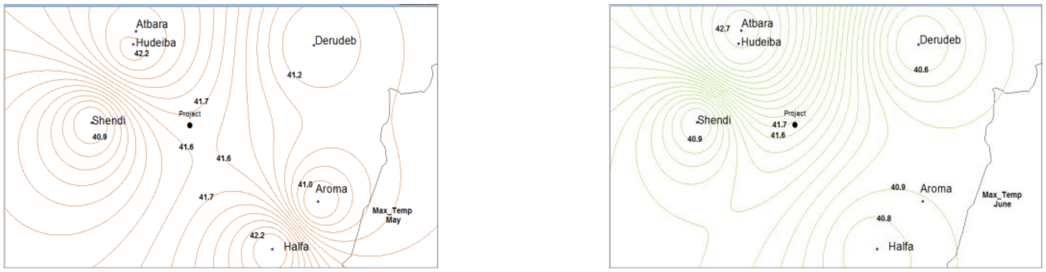
Figure 6. Soil classification according to ... tes Department of Agriculture

The monthly climate parameters values for the ... together with their coordinates using interpolation procedure formed 60 iso maps. Climate parameters obtained include temperature, rainfalls, relative humidity, winds and sun shine hours**.** The developed iso maps simplify the estimation of data required for ETo calculation which is agreed with Savva and Frenken (2002).

Figures 7 and 8 show the monthly maximum and minimum temperature isoclines maps (C°) for the studied area. The results of maximum and minimum temperatures obtained peak values of 41.7 ^{o}C mean maximum temperatures through May and June and 14.2 ^{o}C as a mean minimum temperature in January (Figure 9).

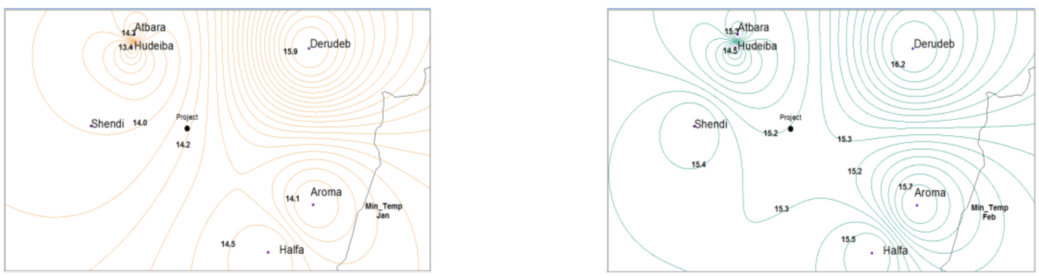
Other monthly iso-climate parameters maps for each station developed in the same manner. The rains during the period of November up to March almost null in all stations and it is notapplicable to produce isoclines maps, however the rains data for the studied area were interpolated and presented in Figure 10.

From the isocline maps, the relative humidity (RH) data were interpolated. The results represent moderate values of RH in rainy months 33 and 39 % during July and August, respectively. Also, winter months (December and January) showed relatively higher RH (38 %). On the other hand, the lowest value of RH registered in April and May 21%. The extracted results for wind speed showed maximum and minimum wind speed in July 268 km day^{-1} and October 190 km day^{-1}, respectively. The isocline maps of the sun shine hours data were interpolated. The results obtained indicated that the sun shine hours ranged from 8.8 to 10.4 hrs. Then the extracted data were processed with CROPWAT 8.0 to estimate ETo over the studied area (Figure 11). The results added that the highest value for ETo is 9.38 mm day^{-1} recorded in June while the lowest value registered in January 5.53 mm day^{-1}.



May **June**

Figure 7. Sample of monthly isocline maps of maximum temperature (C°)



January **February**

Figure 8. Sample of monthly isocline maps of minimum temperature (C°)

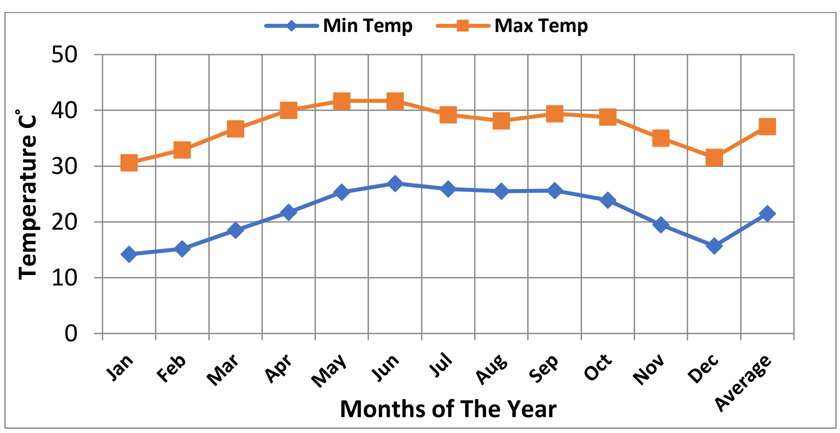


Figure 9. The distribution of maximum and minimum temperatures through the year at studied area

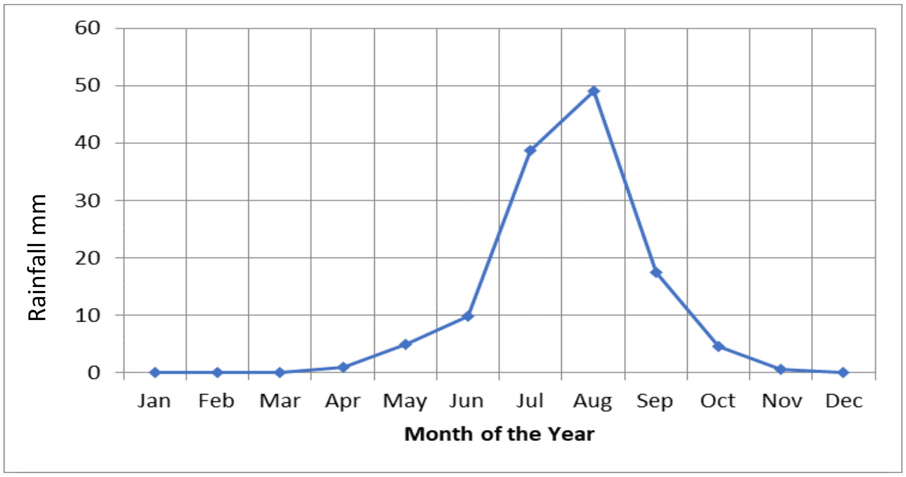


Figure 10. The distribution of rains over the studied area throughout the year

The monthly ETo values for the studied area were used together with crop characteristics to calculate the irrigation requirements for suggested crops. The maximum water needs for the three options are almost the same. Tables 2, 3 and 4 show the summary of the total monthly water needs by each crop and the total water requirement.The crop pattern option 1 was found to be the preferable and optimum opportunity. The maximum monthly water requirement is in August for the three options. The worst condition is 1012 million m^3 $month^{-1}$. Thus, the discharge needs to satisfy the highest water demands is 33.7 Mm^3 day^{-1} in average of 14 working hours per day and the total discharge needed is about 670 m^3 s^{-1}.

Conclusions

Designing irrigation system to estimate water demand and crop water requirement in large-scale areas needs huge climatic, edaphic, topographic and hydrological information. How and where to use this information to obtain reasonable result is time consuming work. Utilization of geographic information systems (GIS) integrated with other applications can be a solution for irrigation system design. This paper indicated the usefulness of geographic information system (GIS) and satellite-based remote sensing (RS) as assistant tools for estimating crop water requirements and irrigation system demand for the large-scale area.

Monthly ETo Penman-Monteith - untitled

Country: Sudan Station: Project
Altitude: 287 m. Latitude: 16.70 °N Longitude: 34.60 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m²/day	mm/day
January	14.2	30.6	38	233	9.4	19.3	5.53
February	15.2	32.9	30	244	9.8	21.7	6.58
March	18.5	36.7	24	250	9.9	23.7	7.88
April	21.7	40.0	21	224	10.4	25.5	8.45
May	25.3	41.7	21	207	10.1	25.0	8.51
June	26.9	41.7	23	257	9.6	24.0	9.38
July	25.9	39.2	33	268	9.0	23.1	8.67
August	25.5	38.1	39	219	8.8	22.9	7.53
September	25.6	39.4	34	209	9.1	22.7	7.58
October	23.9	38.8	30	190	9.3	21.4	6.99
November	19.5	35.0	33	200	9.7	20.0	6.17
December	15.7	31.6	38	240	9.4	18.7	5.71
Average	**21.5**	**37.1**	**30**	**228**	**9.6**	**22.3**	**7.42**

Figure 11. Monthly ETo calculated using FAO Penman-Monteith equation

Table 2. Crops pattern option 1

Crops \ Month	1	2	3	4	5	6	7	8	9	10	11	12	Total (Mm^3 $Month^{-1}$)	Total Area (Hectare)
Broad Bean	605									155	525	863	**2148**	2,797
	151									39	131	216	**537**	
Common Bean	769	87								124	466	860	**2306**	2,797
	192	22								31	116	215	**577**	
SORGHUM Grain						389	845	990	673				**2896**	16,782
						583	1268	1484	1009				**4344**	
Groundnut						251	785	1131	819	37			**3022**	33,564
						752	2355	3393	2456	111			**9067**	
Sunflower							410	843	1099	895	85		**3331**	11,188
							410	843	1099	895	85		**3331**	
Sesame							451	950	1042	331			**2774**	39,158
							1577	3325	3647	1158			**9708**	
Total W/REQ. (Mm^3 $Month^{-1}$)	38	2	0	0	0	147	617	995	903	246	37	47	3032	
Available Water (Mm^3 $Month^{-1}$)	37	159	164	177	150	490	2060	4845	2709	279	118	93	11188	

Table 3. Crops pattern option 2

Crops \ Month	1	2	3	4	5	6	7	8	9	10	11	12	Total (Mm^3 $Month^{-1}$)	Total Area (Hectare)
Wheat	819.4	908.9	497.3								122.2	333.1	**2680.90**	5,594
	409.7	454.5	248.7								61.1	166.6	**1340.45**	
Broad Bean	605									155	525	863	**2148**	2,797
	151									39	131	216	**537**	
Common Bean	769	87								124	466	860	**2306**	2,797
	192	22								31	116	215	**577**	
SORGHUM Grain						389	845	990	673				**2896**	22,376
						777	1690	1979	1346				**5792**	
Groundnut						251	785	1131	819	37			**3022**	22,376
						501	1570	2262	1637	74			**6045**	
Sunflower							410	843	1099	895	85		**3331**	22,376
							820	1685	2198	1790	170		**6663**	
Sesame							451	950	1042	331			**2774**	22,376
							901	1900	2084	662			**5547**	
Total W/REQ. (Mm^3 $Month^{-1}$)	83	52	27	0	0	141	548	861	799	286	54	66	2916	
Available Water (Mm^3 $Month^{-1}$)	37	159	164	177	150	490	2060	4845	2709	279	118	93	11188	

Table 4. Crops pattern option 3

Crops \ Month	1	2	3	4	5	6	7	8	9	10	11	12	Total (Mm^3 $Month^{-1}$)	Total Area (Hectare)
Broad Bean	605									155	525	863	**2148**	2,797
	151									39	131	216	**537**	
Common Bean	769	87								124	466	860	**2306**	2,797
	192	22								31	116	215	**577**	
SORGHUM Grain						389	845	990	673				**2896**	27,970
						971	2113	2474	1682				**7240**	
Groundnut						251	785	1131	819	37			**3022**	27,970
						627	1963	2828	2047	93			**7556**	
Sunflower							410	843	1099	895	85		**3331**	11,188
							410	843	1099	895	85		**3331**	
Sesame							451	950	1042	331			**2774**	33,564
							1352	2850	3126	993			**8321**	
Total W/REQ. (Mm^3 $Month^{-1}$)	38	2	0	0	0	176	642	989	875	226	37	47	3032	
Available Water (Mm^3 $Month^{-1}$)	37	159	164	177	150	490	2060	4845	2709	279	118	93	11188	

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