Integrating GIS and Numeric Weather Prediction Model with Wheat Simulation Model for Optimal Wheat Production Locations in Arid Regions

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Abstract: The upgrade rate of self-sufficiency in wheat depends largely on the amount of water and land to achieve the quantity and proportion of self-sufficiency target. The climatic and soil conditions, however, are dynamic conditions. Hence, these conditions seriously limit the capability of providing the optimum tempo-spatial required data to assist in improving the wheat production unless specialized sensors are utilized along with excessive work. That implies the crucial need of using computer simulation models. The general objective is of this study was to delineate the best location for wheat production in arid regions such as Oman through linking Wheat Simulation Model (WSM) with Numeric Weather Prediction Model (NWPM) in Geographical Information Systems (GIS). The GIS application software used in this study was the ESRI ArcGIS. Four field trials, over two seasons, have validated positively the linkage of the developed WSM with GIS. The developed model can be promoted as a tool of improving wheat cultivation through making the most of available water in wheat production and increasing the growing acreage of wheat in arid regions like Oman.

1 INTRODUCTION

Food security is an important issue especially after the recent food crisis that hit many parts of the world. Food crisis was not limited only to the substantial rise in the prices of food imports, but extended to the lack of universal availability, and then the scarcity and the difficulty of obtaining these goods. One of the most important crops for food in the world is wheat, where more than two thirds of food is provided by cereals (Bushuk and Rasper, 1994) and one third production of cereals is wheat (Carver, 2009). Knowing when to plant wheat crop is one of the most important factors for better emergence timing which leads to better wheat yield especially in arid regions. The emergence time, however, is affected by climatic conditions, soil property and planting depth (Al-Mulla et al., 2014). Moreover, despite the fact that an arid country like Oman has no problem with soil temperature for wheat emergence, Omani wheat growers usually sow almost double number of seeds into a land in order to assure they will get higher wheat production efficiency of that land due to non-emergence of portion of the sowed seeds. That might due to seeds viability and to soil properties especially the optimum soil temperature and soil water potential in addition to planting depth which all play an important role in determining the time of emergence for wheat seedlings. Therefore, in order to increase the wheat production efficiency, there is a need to determine the optimum soil temperature, water potential and planting depth of wheat and so the best time and percentage of wheat emergence can be predicated. However, given the above constraining factors and due to varying values of these factors from time to time and from place to place, estimation of emergence time for wheat will be much easier by using a computer simulation model.

Simulation is a computerized model that describes the behavior of a complex system based on

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a set of data and dynamic variables and interactive components. The Computer simulation models become popular in many natural systems in physics, chemistry and biology, human systems in economics and social science. Biosystems field is considered as one that requires the use of simulation and computer modeling including the predicting the time and percentage of wheat emergence in field applications.

A wheat simulation model (WSM) was developed by Al-Mulla et al., (2014) to predict the time and percentage of winter wheat emergence based on the three above mentioned factors: planting depth, soil temperature, and soil water potential. The developed wheat emergence model is based on the hydrothermal time concept which was proposed and further developed, but for germination only, by Gummerson (1986), Bradford (1990 and 1995) and Cheng and Bradford (1999). The WSM governing equation has the following form:

$$t(f)_E = \frac{\theta_{HT}}{(T - T_b)[\psi - \overline{\psi_b} - (probit(f)\sigma_{\psi b})]} \quad (1)$$

where t(f)E is time from sowing seeds to emergence (days), ψ is soil water potential (MPa), and $\overline{\psi_b}$ and σψb are mean and standard deviation of the base water potential respectively (MPa), T is soil temperature (°C), Tb is the base soil temperature (°C), and probit(f) indicates the number of standard deviations away from the mean that any fraction of the seed population lies. It linearizes a cumulative normal distribution which facilitates modeling efforts (Bauer et al., 1998). The parameter θHT is the hydrothermal time to emergence (MPa degree-days). It can be determined using the following formula:

$$\theta_{HT} = (\psi - \psi_b)(T - T_b)t_E \quad (2)$$

where all parameters explained above.

The parameter probit(f) can be determined as follows:

$$probit(E) = \frac{\psi - \frac{\theta_{HT}}{(T - T_b)t_E} - \psi_b(50)}{\sigma_{\psi_b}} \quad (3)$$

where $\psi_b(50)$ is base water potential for 50% population of planted seeds

The developed WSM also includes the calculation of the maximum percent of emergence (Emax) by using the following equation which works as a threshold for the developed model:

$$E_{max} = c_1 D^2 + c_2 D + c_3 \quad (4)$$

where D is sowing depth (cm), and c1, c2, and c3 are constants related to ψ and T.

The soil temperature and water potential information required for the emergence model are not easy to find for any lands. That's due to the need of using special sensors to measure these factors at time of emergence of the wheat crop. In this study a novel approach is explored in order to utilize the WSM model without the need of using any sensors by finding a better way for extracting the needed model's input data from Numerical Weather Prediction Model (NWPM) which is based on numerical models that deal with set of motion equations. These equations govern the fluid flow partial differential equations (Stensrud, 2007). Hence, by linking WSM with NWPM in Geographic Information System (GIS), the best location of wheat production in arid regions as the Sultanate of Oman can be delineated and that was the main aim of this study. The specific objectives of the projects were: 1) to validate the developed simulation model for predicting the time and percentage of emergence using local field data, 2) to examine the performance of the model using different wheat cultivars, 3) to extract needed data from Numerical Weather Prediction Model (NWPM), 4) to re-design the simulation model by linking it with Geographic Information system (GIS) and NWPM, and 5) to create maps delineating the best location of wheat production in the Sultanate of Oman.

2 MATERIALS AND METHODS

2.1 Field Experiment

Field experiment was conducted at Agriculture Extension Station in Sultan Qaboos University in the Sultanate of Oman (Figure 1) between first of December 2013 until End of May 2014. The field work was divided into two times. In time one, planting started in 1st December 2013 until the end of harvesting stage March 2014. Planting in second time started on 22 January 2014 until 21 May 2014. The field was divided to four lines, the first two lines for time one and the last two lines for time two. Each line was divided to seven 2m × 2m plots. Each plot was divided to ten cultivated lines irrigated by drip irrigation system. The space between one line to another was 20 cm and the wheat seeds were sowed adjacent to the lines with 5cm spacing. Two wheat varieties were used. One of them is local variety which is Coli and the second one was imported from Kuwait which is KW1. The seeds were sowed at two different depths: 2.5cm and 5cm. Hence, the experiment treatment factors are: 2 times × 2 varieties × 2 planting depths. Three replicates for each treatments planting with one control plot of each varieties were conducted. The planting method in the control plots was by broadcasting. Fertilization was applied as recommend by AES staff experience. By which fertilizer was applied two times a week through fertigation system where combination of urea, potassium nitrate and phosphoric acid was applied trough the irrigation system.

2.2 Germination Test

Ten petri dishes were prepared for each variety and in each petri dish a filter paper and ten seeds from each variety were putted and irrigated with water. So, 100 seeds in total for each variety were examined. Germination of seeds was counted and recorded on daily basis.

2.3 Physical and Chemical Soil Analysis

2.3.1 Soil Sampling

One composite soil sample was taken by collecting different soil samples from different plots and mixed together. Then soil was air dried and sieved through 2 mm.

Figure 1: Sultanate of Oman (Source: geoatlas.com).

2.3.2 Moisture Content and Oven Dry Weight

After the soil sample was air _ dried and sieved by 2mm sieve, unspecified amount of soil was taken and its weight was determined before and after drying in oven at 104 °C for 24 hours. Then percentage of moisture content and Oven dry weight were calculated and result used in soil texture calculation.

2.3.3 Soil pH, EC and SAR Measurements

Paste saturation sample was prepared and soil solution was extracted by air vacuum for Electrical Conductivity (EC) and pH measurements using electrical electrode. For Sodium Absorption Ratio (SAR), concentration of Sodium (Na), Calcium (Ca), and Magnesium (Mg) were measured using ICP. To find SAR value, the following equation was used:

$$SAR = \frac{[Na]}{\sqrt{[Ca + Mg}} \tag{5}$$

2.3.4 Soil Texture

Soil sample was air-dried and sieved by 2mm sieve. From sieved soil, 50g of soil was assigned into a baffled stirring cup with 10ml of 0.5N sodium hexametaphosphate and distilled water was added until half fill of the cup. The mixture was stirred for five minutes and transferred to 1000ml graduated cylinder which was filled with distilled water until 1000ml mark. The suspension was mixed and at the end of 20 second from mixing, the hydrometer was inserted. The first reading of hydrometer was recorded after 40 seconds and also temperature of suspension was recorded by the thermometer. Then, the hydrometer was removed and re-shacked again. After two hours, the reading of hydrometer and temperature were recorded. The percentage of each particle size was calculated according to these equations:

Corrected Hydrometer Reading:

HRc = HR + (0.2 for every 1°C above 20°C) (6)

$$\%silt = \frac{HRc\ at\ 40\,\text{sec} - HRc\ at\ 2\ hr}{ODW} * 100 \tag{7}$$

$$\%Clay = \frac{HRc\ at\ 2\ hr}{ODW} * 100 \tag{8}$$

$$\%Sand = 100 - (\%Silt + \%\ Clay) \tag{9}$$

2.4 Irrigation

Drip irrigation was used in the study. Ten drip lines were crossing the plots with 20cm spacing between the emitters. Water required was calculated based on crop evapotranspiration for each stage of wheat development. The historical data like daily maximum and minimum soil temperature and humidity, wind speed and the meteorological data for Seeb weather station were used. Visual basic in Excel sheet was used to create sheet for reference water requirement (ETo). The sheet is based on Penman – Monteith method. To determine the time of irrigation, the discharge of water from meter was recorded. Hence, the time of irrigation was calculated by dividing volume of water required by the discharge.

2.5 Sensors

The inputs parameters including water potential and soil temperature, for wheat simulation model can be obtained from the sensors installed in the field. A 229 heat dissipation sensor from Campbell Scientific Company, USA, is used to measure water potential indirectly using principle of heat dissipation. The principle of heat dissipation is whenever there is water potential gradient between sensors and the surrounding soil, water movement between sensor and soil take certain time to reach equilibrium. Hydraulic Equilibration time depend on magnitude of water potential gradient and hydraulic conductivity. The changes in water content of sensor ceramic matric lead to change in the thermal conductivity of sensor/ soil complex. There is exponential relationship between water content and thermal conductivity. As water content in the ceramic sensor increase, the thermal conductivity increase. A 229 heat dissipation sensor is porous ceramic cylindrical shaped with thermocouple and heating element at the middle of the cylinder. It has the ability to measure a wide range of matric potential from -10 to -2500KPa and it is compatible with most Campbell Scientific data logger and multiplexer. Also, it is known by long lasting without need for maintenance. The 229 should be installed horizontally at the desired depth and good contact between the ceramic cylinder and soil must be exist (Instruction manual of model 229, Campbell Scientific Inc.). Soil water potential can also be measured by using MPS2 from Decagon Devices Inc., USA. MPS2 is ideal sensor for a range of water potential measurement between -0.01 and -0.5 MPa and soil temperature between -40 and 60C (Decagon Devices Inc.). A 5TE sensor from Decagon devices, USA, is used to measure volumetric water content, soil temperature and electrical conductivity. It measures the three parameters independently. The volumetric water content is obtained by measuring the dielectric constant of the media using electromagnetic field supplied from the sensor with 70 MHz while the soil temperature is obtained from thermistor which is installed at surface of the sensor with a range of readings of -40 to 50°C. Electrical conductivity is obtained by using stainless steel electrode array and the reading is taking within the range of 0 to 23 ds/m. The sensor is easily installed in the field through pushing it directly to undisturbed. EC is measured by applying alternating current to two electrodes and measuring the resistance between them soil (Decagon Devices Inc.).

2.6 Linking WSM to GIS

To link the wheat simulation model in GIS, soil temperature and volumetric water content raster layers were required as input for the model and they were extracted from the European Centre for Medium-Range Weather Forecasts (ECMWF) website which is an independent intergovernmental organization established in 1975. The Centre provides a catalogue of forecast data worldwide that can be purchased by businesses and other commercial customers for national community. Different spatial analysis tools in GIS were used to create the final emergence map mainly rater calculator and reclassifying tools (Figure 2).

2.7 Statistical Analysis of Physical Characteristics of Wheat

Physical characteristics of wheat like length of plant, number of spikes per plant, number of seeds per spike and weight of 100 seeds of each variety were examined at the late season of each planting time. Plant height was measured by taking average length of random selection of plants using meter tab from the soil surface to the begging of the spike. The average plant length in each plot was recorded. Random plants were also selected to find out number of spikes in it and average numbers of seed in each spike were counted. After the seeds removed from its spike, 100 seeds from each plot was weighed using digital scale. For statistical analysis, ANOVA for single factor was used to examine the differences among each factor.

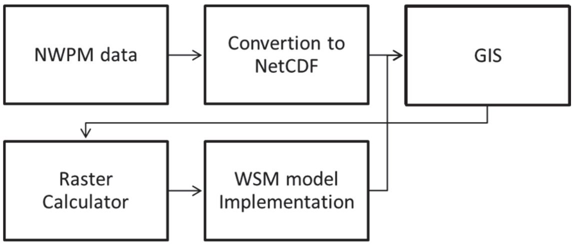

Figure 2: Flowchart of Creating Wheat Prediction Model in GIS.

3 RESULTS AND DISCUSSION

Germination was started after second day of planting. For local variety (Coli) germination was 99% in second day and 100% in third day. For KW1, germination was 46% in second day and after second day till day six of planting, germination was stopped at 60%.

Soil Texture Class for planting field is silt loam which is medium textured soil. For wheat production, the best soil type is well drained fertile loamy soil to sandy loam soil (DAFF, 2010). Electrical conductivity for paste soil extract is 478 µS\cm, Sodium absorption ratio (SAR) is 2.35 and pH is 8. The best range of soil pH for wheat production is between 6 and 7.5 (DAFF, 2010). The pH value in this study exceeded the optimum range a little bit. Alkalinity affects wheat production negatively in two ways by decreasing water infiltration and decreasing availability of micronutrients. Since that the solubility of Iron (Fe), manganese (Mn), copper (Cu) and zinc (Zn) decrease with increasing soil pH. However, deficiency of the last three ions due to alkalinity has not severe effect in wheat production area (Heyne, 1987). Based on the EC and SAR values, soil was classified as non-saline and non sodic soil. It was normal soil and suitable for wheat production.

Crop evapotranspiration and Irrigation Scheduling for each plant stage are presented in Table 1 for planting time one and two. As expected, for first time of planting, crop coefficient (Kc) started with small value but it increased as plant grown and developed and then decreased at late season as plant senesce. The crop water requirement (ETc) followed the same pattern of the Kc. Because the plant need more water at growth and developing stages, the duration of irrigation increased until the late season where it decreased and stopped for one week before harvesting. The ET_0 and ETc values increased during time two of planting than time one due to the increase of air temperature. That resulted in increasing the duration of irrigation supply in time tow more than in time one.

Since WSM requires soil water potential as one of the input data and since both sensors the 5TE and MPS-2 measure volumetric water content for, there was a need to convert these sensors data into water potential. A relationship between soil's volumetric water content and water potential were obtained. By which a regression equation of calculating water potential from volumetric water content was found as follows:

$$\Psi = -20.208\ wc^2 + 11.747x - 1.7176 \qquad (10)$$

Where Ψ is soil water potential (MPa) and wc is soil water content (%).

The time of emergence equation of the WSM has a probit parameter. It is a value that is used to indicate the number of standard deviation away from the mean that any fraction of seed population lies. Also, it is used to linearize a cumulative normal distribution which makes the model easy to work (Al Mulla et al., 2014; Bauer et al., 1998). Since it is not possible to calculate the probit value in GIS directly, relationship was found between emergence percentage and the probit value which can be expressed in the following equation:

$$Probit = 0.3383\ln(E) - 1.996 \qquad (11)$$

where Probit is probit value and E is emergence percentage (%).

Figure 3 shows emergence results from time one. Emergence started after day 4 from planting for all treatments and reached maximum emergence at day 12 after planting. The maximum percentage was achieved for Coli variety at 2.5 cm planting depth which was 75 % at day 12 after planting while at planting 5 cm depth, the maximum emergence was 62 %. For KW variety, at planting depth 2.5 cm, the maximum emergence was achieved after day 12 with 53 % and at planting depth of 5 cm, the maximum emergence was 36 %. Emergence results of time 2 are presented in figure 4. The emergence of both varieties started after day 5 from planting and reached the maximum at day 12 from planting. Coli variety had higher percentage of emergence than KW variety where at 2.5cm planting depth it reached the highest percentage among other treatments with 77%. The KW variety reached its higher emergence percentage at shallow planting depth (50%) in comparison to deep planting depth (44%).

The WSM predictions for the wheat to start emerging were 5 days after planting (DAP) in time one and 5 DAP in time two. While in the field it

Table 1: Evapotranspiration and Irrigation Scheduling for Times one and two.

Stage Name	Satge Duration Days		Kc		Average ET_0 mm/day		Average Etc mm/day		Volume m^3		Irrigation Time min	
	Time 1	Time 2	Time 1	Time 2	Time 1	Time 2	Time 1	Time 2	Time 1	Time 2	Time 1	Time 2
Initial Stage	20	20	0.4	0.4	3.3	3.6	1.32	1.4	0.07	0.08	1.3	1.4
Growth and Branching	30	30	1	1	3.1	4.5	3.1	4.5	0.17	0.25	3.1	4.6
Completion of growth and Flowering	30	30	1.2	1.2	3.5	5.4	4.2	6.5	0.24	0.36	4.3	6.7
Composition and Grain Filling	30	30	1	1	4.7	6.7	4.7	6.8	0.26	0.38	4.8	7
Late Season	15	15	0.4	0.4	5.3	8.8	2.12	3.5	0.12	0.20	2.1	3.6

took 4 DAP in time one and 5 DAP in time two. The DAP to reach 50% emergence was predicted by WSM as 6 DAP and 6 DAP in both times one and two. In the field, the wheat reached 50% emergence after 7 DAP and 6 DAP in time one and time two. The maximum percentage achieved in the field, for time 1, was 74% whereas WS prediction was 67% while for time 2, the maximum percentage was achieved in the field was 77% whereas WSM prediction was 80%. The DAPs to reach maximum emergence was predicted by the WSM as 7 DAP while in the field it was achieved after 11 DAP for time 1. For time 2, the SWM prediction was 6 DAP in the field it was achieved after two more days which was 8 DAP.

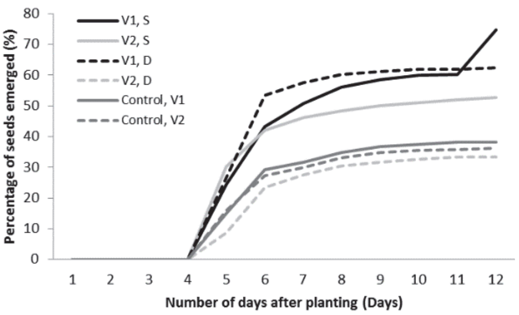

Figure 3: Wheat seed Emergence for Time one.

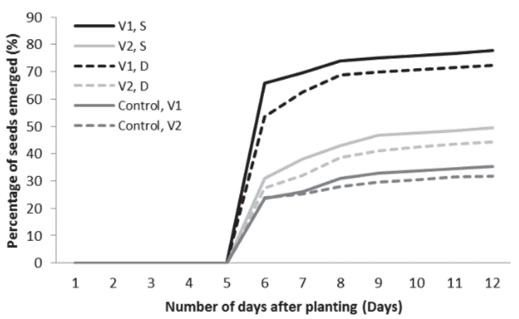

Figure 4: Wheat seed Emergence for Time two M.

The soil temperature and volumetric water content data at level 1were extracted from ECMWF by selecting a month long (October 2013) of the required data with time steps of 24 hours. Equation 12 was used in the raster calculator to find soil water potential from the volumetric water content layer extracted from ECMWF. The data format was in Network Common Data Form (NetCDF), so they needed to be converted to raster data format for GIS. That was done by selecting "Make NetCDF Raster Layer" which is a sub menu under Multidimintion menu of ArcToolbox.

After raster layers of soil temperature and water potential were created from NetCDF file, coding the equations of hydrothermal time and maximum emergence was done using raster calculator. Equations of maximum emergences are based on certain range of temperature and water potential with a total of 23 conditions. Hence, 23 raster layers of pixels that match with emergence conditions have certain values of maximum emergences and therefore they made to appear in colored pixel. However, the other pixels that do not match the emergence conditions of emergence have no data. To merge all emergence raster layers in one layer to be used in the final equation of time of emergence, the no data pixels were converted to zero value using Reclassify tools from spatial analysis. All reclassified emergence raster layers were combined in one raster layer using addition tool in raster calculator producing a single layer map. Figure 5 shows the outcome of the GIS-Linked WSM modified model for the Arabian Peninsula region after extracting the NWMP data from the ECMWF.

4 CONCLUSIONS

Wheat is one of the most important crops for food in the world including arid regions as the Sultanate of Oman. For arid regions, It would be especially useful to develop a method that can increase wheat production location but with minimum possible water consumption. By integrating GIS technology, a Wheat Simulation Model (WSM) was further developed for optimal wheat production location in arid regions. WSM was tested with field data and the effectiveness of the model was proven. The study illustrates a good example of GIS application for solving spatial and temporal crop production optimization problem. By which, it becomes possible to delineate (map) the WSM outcome that can cover any part of world including arid regions by eliminating the need of using any sensors to run the simulation.

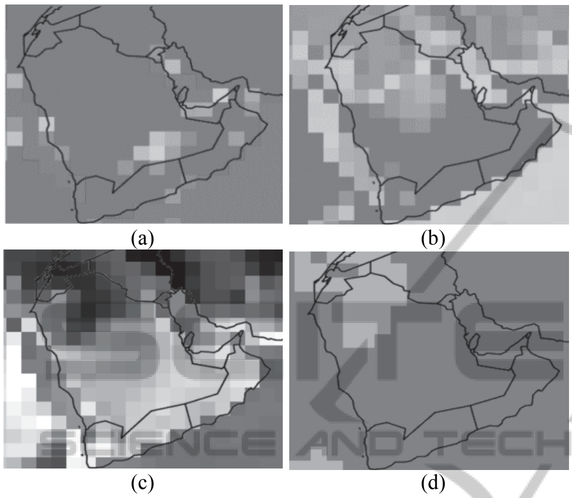

Figure 5: GIS linked WSM outcome: (a) soil Water Potential, (b) Soil temperature, (c) Hydrothermal time factor and (d) Time to emergence.

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