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ORIGINAL ARTICLE

Remote Sensing Inputs to SWAT Model for Groundwater Recharge Estimates in Kuwait

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ABSTRACT

The Soil and Water Assessment Tool (SWAT) model was used to provide continuous (1998-2006) simulation of overland flow, channel flow, transmission losses for the for the Raudatain watershed in northern Kuwait, and the Umm Al Aish watershed in central Kuwait covering approximately 50% of the Kuwaiti landscape. Inputs required for the SWAT model were extracted from readily available global remotely sensed satellite datasets. These include precipitation from the 3-hourly TRMM data, stream networks and watershed boundaries from SRTM 90 m data. Preliminary results from TRMM NASA TOVAS suggest that northern and central Kuwait receive an average annual precipitation of ~210 mm/year, of which 30mm could potentially recharge the shallow aquifers in the area. Applications similar to those presented here that utilize SWAT modeling and call on readily available remotely acquired data are extremely valuable for a country like Kuwait and similar areas/settings world-wide. Such models and approaches can potentially provide alternative solutions for the assessment of sustainable water resources, where traditional data required for understanding these hydrologic systems are absent or deficient over the spatial and temporal domains of interest.

Key words: SWAT, Rainfall-Runoff Modeling, Kuwait, Recharge.

Introduction

The arid lands in the Middle East have long since experienced issues pertaining to the scarcity of fresh water resources. The presence, abundance, or absence of these fresh water resources had a direct effect on the distribution of population in these areas and the development of these societies throughout the years. In recent years, many of these arid countries of the Gulf area experienced a general sporadic growth in their population, largely due to the discovery of oil and the revenues that come with it. Kuwait is one of these countries, the population of Kuwait was 350,000 in 1970 and now it is approaching 3.2 million. Additional water fresh water resources are needed to support this increasing population.

In Kuwait as is the case with many of the arid regions in the Middle East, the sources of fresh water are one of two: (1) fossil water that was deposited in the previous more humid climatic conditions that recharged the major aquifers, and (2) modern meteoric precipitation that is usually found in shallow aquifers. It is important to be able to: first step to achieve the development of sustainable utilization of Kuwait's groundwater resources is to estimate the spatial and temporal distribution of precipitation over Kuwait, and to quantify the partitioning of precipitation into runoff, recharge, and evapo-transpiration.

Quantification of the hydrological budget is extremely difficult over large spatial and temporal domains through direct observations, and is often hampered by the paucity or absence of field data including soil maps, precipitation data, stream flow data, etc. Luckily, with time more and more remote sensing data sensors are

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being deployed, more regions of the Earth's surface are covered temporally and spatially. With these advances, remote sensing data sets are becoming more extensively used to estimate various critical parameters (e.g., landuse - landcover, precipitation, soil types, evaporation and evapotranspiration) (Anderson *et al*., 1976; Beven *et al*.; 1988, Menenti *et al*., 1989; Menenti, 1993; Bastiaanssen *et al*., 1994; Bastiaanssen, *et al*., 1996; Bastiaanssen, *et al*., 1998a and 1998b; Bastiaanssen, *et al*., 2005). In the present study remote sensing technologies were used to make first order estimates of recharge to fresh water shallow aquifers for the purpose of developing sustainable water management scenarios.

Geologic Setting

Kuwait has a two-tier aquifer system comprising the Dibdibah Formation of the Kuwait Group at the top and the underlying Dammam Formation, which supports the lower aquifer. The Kuwait Group has a shallow aquifer system of Quaternary age, which is unconfined in nature. Lithologically it comprises silt and gravelly sand. The Dammam Aquifer underlies the Kuwait Group; it is a chalky dolomitic limestone of middle Miocene age, which is under confined conditions, however upward leakages from the Dammam Formation are reported at places (Abusada, 1981). The groundwater level varies from 90 m above mean sea level in the southwest to zero at the Arabian Gulf in the northeast. (Al-Ruwaih *et al*., 2000) The flow follows the regional northeastern dip (Figure 1). The groundwater quality from these aquifers varies from brackish in the southwest to highly saline in the northeast. The brackish water in the south and central portions of Kuwait have a TDS value around 4000 parts per million (ppm,) and is used for irrigation and landscaping, but in the north the water is highly saline with TDS values exceeding 130,000 ppm (Burdon and Al Sharhan, 1968, Himida and El-Yaqubi, 1979), which renders it unfit for direct use.

Two large watersheds are the subject of this study, the the Raudatain watershed in northern Kuwait, and the Umm Al Aish watershed in central Kuwait. The first occupies an area of 3696 km^2, the second 2612 km^2. Collectively, the two watersheds constitute approximately 35% of the total area (17,800 km2) of Kuwait. The two watersheds were selected because of their large areal extent and because shallow fresh water lenses were reported within the Dibdibah Formation of the Kuwait Group. These lenses most likely originated from modern precipitation. In this study we apply continuous (1998-2006) rainfall runoff models to estimate to a first order average annual recharge in these two major watersheds.

Methodology

In this study a catchment-based, continuous, semi-distributed hydrologic model to quantify the spatial and temporal distribution of surface runoff and potential ground water recharge was estimated. The Soil and Water Assessment Tool (SWAT) model provides estimates of the various partitions (e.g., runoff, recharge, transmission losses, evaporation) of the hydrologic cycle (Arnold *et al*., 1998; Arnold and Fohrer, 2005;). The SWAT model was chosen for the following reasons: (1) the model is an open source code giving the user the flexibility for making modifications as needed, (2) it simulates hydrologic processes continuosly and not just event by event which gives recharge estimates over large time frames (3) the model allows futuristic simulations which can aid in water management decisions.

The following series of data sets were used as inputs into the model: (1) 3-hourly precipitation data (1998-2006 – Tropical Rainfall Measuring Mission (TRMM)), (2) digital elevation model – global Shuttle Radar Topography Mission (SRTM), (3) lithologic maps (Figure 1), (4) landuse maps – derived from Climatic Atlas of Kuwait (Figure 2), and (5) meteorological data of air temperature and wind speed obtained from online sources, namely the Directorate General for Civil Aviation in Kuwait (DGCA, 2009) (Figure 3). SWAT automatically integrates these data sets to provide temporal and spatial estimates of the water balance budget in the investigated basins.

The U.S. Department of Agriculture's - Soil Conservation Service method (SCS, 1972) is incorporated into SWAT to calculate initial losses and runoff in the sub-basins. The method is suited for humid, semi-arid, and arid conditions (SCS, 1985) and has been successfully applied to several ephemeral watersheds in arid environments, which resemble Kuwait in hydrogeologic characteristics (eg., climate, topography, and land use) (Milewski *et al*., 2009; Saif ud din *et al*., 2007; Osterkamp *et al*., 1994). The SWAT theory manual provides details on the equations and concepts incorporated in SWAT to partition the hydrologic cycle. Here we present an overview on the important processes (Neitsch *et al*., 2005). The curve number used in the SCS method is a function of the antecedent moisture condition (AMC), the land use, the hydrologic condition, and the hydrologic soil type. Runoff in sub-basins occurs after rainfall exceeds an initial abstraction (*Ia*) value. Rainfall excess, *Q*, in the SCS method is related to the effective precipitation, (*P – I* maximum potential retention value, *S*, as shown by Eq. (1):

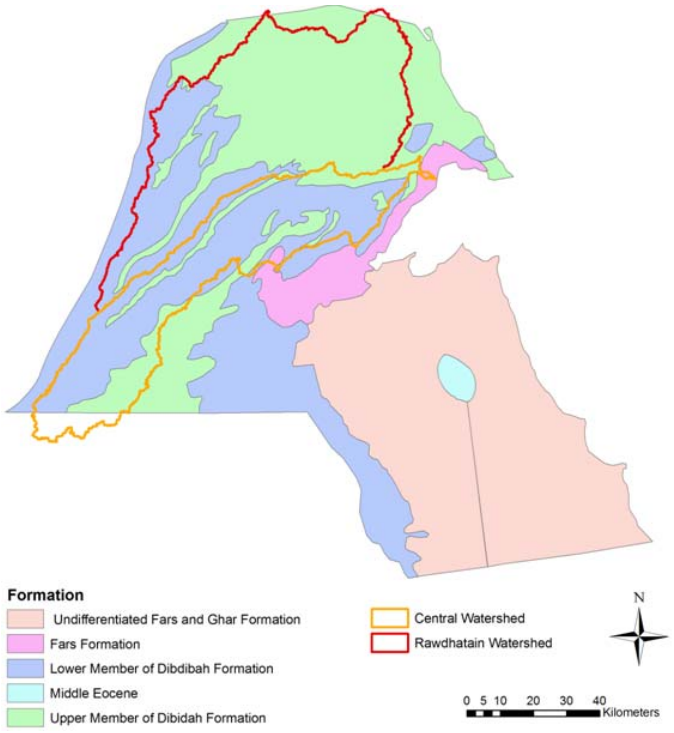

Fig. 1: Geological Map for Kuwait showing the distribution of outcrops and the investigated watersheds in northern and central Kuwait.

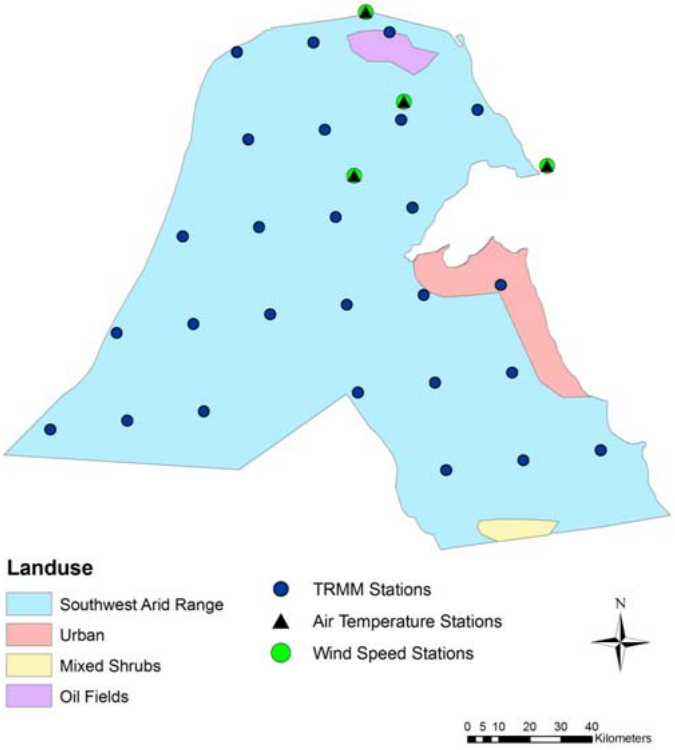

Fig. 2: Landuse Map for Kuwait. Also shown are the locations of meteorologic stations and TRMM stations.

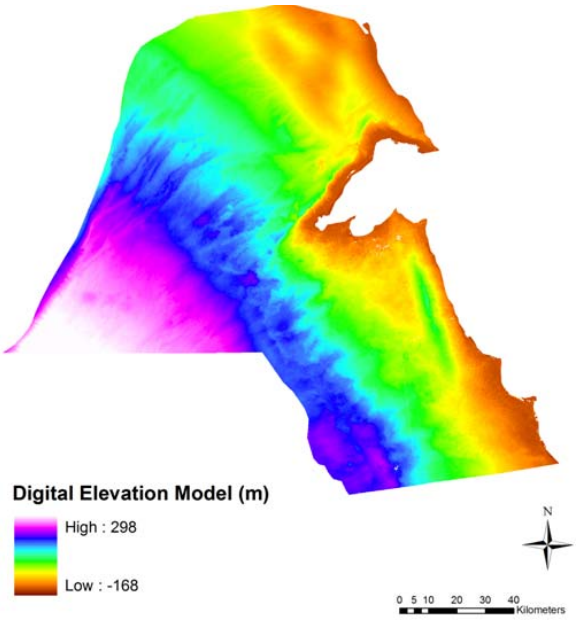

Fig. 3: Color-coded digital elevation data extracted from SRTM data

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \tag{1}$$

Here *Q*, *P*, *S*, and *Ia* are all in inches. The maximum potential retention, *S*, is a function of an empirical curve number coefficient, *CN*, where

$$S = \left(\frac{1000}{CN} - 10\right) \tag{2}$$

The initial abstraction is suggested by the SCS to be approximately 20% of the maximum potential retention value,

$$Ia = 0.2 \times S \tag{3}$$

Transmission losses were computed as a function of channel dimensions, travel time, and hydraulic conductivity as shown by Eg. (4), where *Kch* is the hydraulic conductivity, *TT* is the travel time, *Pch* is the wetted perimeter of the channel, and *Lch* is the length of the channel.

$$Tloss = K_{ch} * TT * P_{ch} * L_{ch} \tag{4}$$

Transmission losses are understood to contribute to the shallow aquifer (Lane, 1983). Evapotranspiration (ET) is calculated using the Penman-Monteith method (Monteith, 1981). Channel routing processes and parameters are estimated by the Muskingum routing method (McCarthy, 1938), where the Manning's coefficient for flow in the channel is used to calculate the rate and velocity of flow in a reach segment for a given time step according to Eqs. (5) and (6).

$$q_{ch} = \frac{A_{ch} * R_{ch}^{(2/3)} * slp_{ch}^{(1/2)}}{n} \tag{5}$$

$$v_c = \frac{R_{ch}^{(2/3)} * slp_{ch}^{(1/2)}}{n} \tag{6}$$

Here *q ch* is the rate of flow in the channel (m^2 flow in the channel (ms*lpch*),

*Rch*3 /s), *Ach* is the cross-sectional area of the is the hydraulic radius for a given depth of flow (m), and is the open-channel bed slope along the channel, *n* is the Manning's coefficient for the channel, and *vc* is the flow velocity (m/s). The majority of parameters relating to soil and landuse properties were extracted from existing databases or given average default values based on standard reference values (Gheith and Sultan, 2002; Milewski *et al*., 2009; Neitsch *et al*., 2005). The saturated hydraulic conductivities of soils were estimated from the field data. The groundwater recharge to the shallow aquifer is based on the percolation at the bottom of the soil profile at the end of each time step and the transmission losses. Eq. (9) shows how groundwater recharge is computed in SWAT:

$$w_{rchrg,i} = (1-exp[-1/\delta_{gw}]) * w_{seep} + exp[-1/\delta_{gw}] * w_{rchrg,i-1}$$

Where, *wrchrg*, is the amount of recharge entering aquifer of a given day, *d* time or drainage time of the overlying aquifer, *wseep* the bottom of the soil profile on a given day, and *w* entering the aquifer on a given day. is the delay *gw* is the total amount of water exiting *rchrg,i-1* is the total amount of recharge. Due to the hyper-aridity of the area, sparse vegetation, and highly conductive surface material in the valleys, the recharge of the alluvial aquifers was estimated mostly as the transmission losses and to a lesser extent from overland infiltration.

Model Construction

To quantify the various facets of the hydrologic cycle, a rainfall-runoff model was constructed using the Soil and Water Assessment Tool (SWAT) developed by the Blackland Research Center (Arnold *et al*, 1998; Arnold and Fohrer, 2005). SWAT compiles the digital geographic datasets into a spatially uniform grid. The major inputs into this hydrologic model are: digital elevation models (DEM), landuse, soils, meteorological datasets (precipitation, air temperature, relative humidity, wind speed, solar radiation), soil parameters, model parameters, and calibration data.

Data Preparation

The first stage in the construction of the hydrologic model was creating the various input datasets from the multiple sources. In order to run SWAT model a DEM was generated to identify the drainage network and define the watershed boundary, as well as drainage morphology (areas, slope, lengths, etc.) for the main basins and valleys. Geologic and landuse maps were used for mapping the soil and landuse types (Atlas of Kuwait, 2000). Rainfall data was obtained from the Tropical Rainfall Measuring Mission (TRMM) satellite measurements using 3B42.v6 products. All datasets were processed and reprojected to Universal Transverse Mercator (UTM), Zone 38 and 39.

The model was used to simulate the results of the Central and Northern Watersheds in Kuwait (Figure 1. The results of the model are summarized in Table 1 given below.

Table 1: SWAT model results for 1998-2006

Rawdhatain Watershed			
Parameter	Annual (x106m3)	% of Precipitation	Total (1998-2006) (x106m3)
Area (km2)	3696.4	-	-
Precipitation	837	-	7533
Surface Runoff	220	26	1980
Transmission Losses	16	2	144
Initial Losses	617	73	5553
Aquifer Recharge (5% of Initial Losses)	46.8	5.5	421.2
Central Watershed			
Parameter	Annual (x106m3)	% of Precipitation	Total (1998-2006)
Area (km2)	2612.7	-	-
Precipitation	551	-	4959
Surface Runoff	150	27	1350
Transmission Losses	4	1	36
Initial Losses	401	72	3609
Aquifer Recharge (5% of Initial Losses)	24	3.6	216

Results and Discussion

First-order estimates of average annual runoff and recharge for large portions of Kuwait were obtained using continuous (1998-2006) rainfall runoff models for the Raudatain watershed in northern Kuwait, and the Umm Al Aish Watershed in central Kuwait. The adopted methodology was intended to overcome problems arising from the paucity of field data, namely precipitation, stream flow data and topographic data. We used 3-hourly (0.25° x 0.25°) TRMM precipitation data as a substitute to rain gauge data and SRTM data to derive the distribution of stream networks and watersheds, a substitute to information derived from topographic sheets.

Analysis of 3-hourly precipitation data shows that the average annual precipitation over the northern watershed is 841 x $10^6 m^3$ and that over the central watershed is 551 x $10^6 m^3$. One might not expect a 1:1 correspondence between the TRMM and rain gauge or actual rainfall given the fact that the rain gauges provide local measurements, whereas the TRMM integrate observations over much larger domains (covered area: 0.25° x 0.25°). Despite the observed general spatial aagreement between the gauge/real world and TRMM-derived precipitation, there seems to be discrepancies that cannot be attributed solely to differences in the footprint size. This is most likely due to the fact that the satellite radar sensors can misidentify a variety of Earth surfaces for precipitating clouds (e.g., Bauer *et al*., 2002) giving an incorrect indication for light rainfall (Turk *et al*., 2003).

Our analysis of the TRMM data showed that the overwhelming majority of the precipitation is in the months of November through February. Throughout the examined period, approximately 90% of the total precipitation was detected during these months, a time of the year, where temperatures are relatively low (average temperature: 55° F) and hence evaporation is reduced.

Aquifer recharge estimates were based on the transmission losses and a portion of the initial losses. All transmission losses were assumed to contribute to aquifer recharge due to high infiltration capacities and minimal evaporation in the streams. Initial losses are high for both watersheds, amounting to 74% of the total precipitation over the northern watershed, and 73% for the central watershed. This is not surprising given the fact that the soil types in both watersheds are largely alluvial deposits with high infiltration capacities. One would expect that for these soils, infiltration will be high, and hence evaporation will be reduced to a minimum. This is apparently the case, infiltrations as high as 9 m/day were reported from the Raudatain watershed (Parsons, 1964). Using a conservative estimate for infiltration (5% initial losses)(Flint *et al*., 2000; Havasi and Flint, 2001; Bawahir and Wood, 1995), we obtain minimum estimates for recharge of 31 x $10^6 m^3$, and 20 x $10^6 m^3$ for the northern and central watersheds.

Runoff is relatively large for both watersheds, amounting to 26% of the total precipitation for the northern watershed, and 27% for the central watershed. That is a little surprising given the fact that the landscape is largely formed of alluvial aquifers with high infiltration capacities and a gently sloping topography. Based on visual comparisons of storm events that produced little to no runoff when the model produced runoff we believe these estimates are maximum estimates and thus the estimated recharge amounts should be viewed as being conservative. Transmission losses were also smaller than expected and compared with similar geographic areas (Gheith and Sultan, 2002).

It is worth mentioning that the trial run of the model based on the data generated from remote sensing datasets shows a good correlation with other estimates shown for the region (Saif ud din *et al*., 2007). Results demonstrate the groundwater potential in Kuwait. Conservative estimates indicate that annual recharge for the investigated watersheds amounts to approximately 50 x 10^6 m^3. Additional work and field data are required to extend these methodologies to the entire Kuwaiti landscape and to refine these preliminary estimates by acquiring additional field and remote sensing data for calibration purposes.

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