Modeling of Groundwater Behavior using GIS and ModFlow Software : Case study of Al Kharj Region – Al Kharj Saudi Arabia

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Abstract— The great demand for water in the Kingdom of Saudi Arabia as well as the lack of rain in most regions of the kingdom, which is called the dry regions, requires an urgent need for groundwater resources. It is necessary to explore it and estimate its quantity and behavior by using spatial analysis tools such as Geographic Information Systems (GIS) and specialized simulation and modeling programs like ModFlow software. The creation of geo-database and modeling of shallow groundwater provide useful information about the quantity and quality of water resources taking into account flood disaster risk and wastewater pollution of the main wadis (valleys and basins). The application of GIS and ModFlow software allow also help in the understanding of the possible interconnections between the flood on the surface and the seepage area taking into account the lithology of the main sedimentary rock and soil layers nearby the surface. This articles presents the results of an applied research project that describes the methods, developed within the Research Center of the College of Engineering of Salman bin Abdulaziz University, to model the behavior of groundwater taking into account the flood-prone areas on the surface, to estimate the quantity of water that might percolate into groundwater and propose the best locations for the hydraulic works needed on the main wadis. Based on the increasing volume of wastewater from the North West and South East of the study area, and by using GPS to quantify the water table and water quality in many shallow wells in this region, this article presents a methodology that might be useful for pollution forecasting, planning and management with the help of pollution hazard maps.

Index Terms— Groundwater, GIS, RS, ModFlow, Geo-processing, Pollution Forecasting.

2 Introduction

The great demand for water in the Kingdom of Saudi Arabia as well as the lack of rain in most regions of the kingdom, which is called the dry regions, requires an urgent need for groundwater resources. It is necessary to explore it and estimate its quantity and behavior by using spatial analysis tools such as Geographic Information Systems (GIS) and specialized simulation and modeling programs like ModFlow software. Nowadays, GIS is considered as an important tool for building spatial database which can be integrated with ModFlow software to simulate groundwater by taking into account many spatial layers (geomorphology, land use, land cover, hydrology, hydrogeology, geology and drainage network, and so on). Groundwater is the largest available source of fresh water and finding out groundwater potential zones, monitoring and conserving groundwater resources have become very crucial (Rokade et al., 2004 [1]). GIS spatial database provides useful information on geology, geomorphology, structural pattern and recharging conditions, which logically define the groundwater regime of an area (Rokade et al., 2007 [2]). Remote sensing techniques using aerial photographs and satellite imagery has proved significant in the field of hydro-geological investigation (Chatterji and Singh, 1980 [3]).

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This paper highlights the role of GIS in the compilation of various data as digital maps, and the integration with the numerical modeling using ModFlow software (Rokade et al., 2007 [2]) which can model the expected estimate groundwater resources in Al Kharj area of Saudi Arabia. In order to protect the urban population against flood and to manage the huge amount of runoff, it is necessary to propose an artificial recharge involving new technologies such as GIS and remote sensing (Chatterji and Singh, 1980 [3]). The groundwater model from ModFlow cannot only be linked with GIS, it can also be integrated into a web environment with GIS Technology (Shiqin et al., 2000 [4]). Many applications have been carried out based on ModFlow software to assess groundwater resources. One of these applications is the model that used ModFlow to predict the change in the groundwater system of El-Moghra Aquifer in Wadi El-Farigh (MAIWF) in Egypt (Youssef et al., 2012 [5]). According the results of this model, the maximum groundwater decline applying the current exploitation strategy will reach 30 m after 7 years while the decline will reach 35 m in case of increasing the pumping rate by 15%. In addition, the construction of the proposed new irrigation canal in the North East direction of MAIWF will improve the groundwater recharge (maximum groundwater decline of 16 m). The concept of integrating remote sensing and GIS has proved to be an efficient tool in integrating urban planning and groundwater studies in lower Sanjai Watershed, Jharkhand (Binay and Uday, 2010 [6]). Hydrogeomorphological studies coupled with hydrogeological and structural/lineament have proved to be very effective tool to discern groundwater potential zones. The same concept has been applied to assess the groundwater potential in the basement terrain of Ekiti area, South-West of Nigeria (Talabi and Tijani, 2011 [7]). The thematic maps of geology, geomorphology, lineament, slope, drainage and drainage density were prepared and integrated using ArcGIS 9.1 software to produce the groundwater potential map of the study area. The GIS evaluation produced a groundwater potential map in which the study area was categorized into zones (very good, good, moderately good and poor) from the south to the north of the study area. Integration of groundwater flow modeling and GIS represents an innovative way to help decision making by improving modeling methods in hydrology and water resource management (Arshad and Zulfiqar, 2012 [8]). In this sense, GIS application has provided help in an accurate and manageable way of estimating model input parameters, integration of disparate data layers, conceptualizing of model recharge and discharge sources and visualization of the model output. GIS-based modeling, as a side benefit, also provides an updated database that can be used for non-modeling activities such as water resource planning and facilities management. In addition, remote sensing and GIS have important role to visualize the main localities in which an artificial recharge of the groundwater aquifer may be useful (Murugiah and Venkatraman, 2013 [9]). In order to control the quality of groundwater, the huge quantity of wastewater investigated in many places within the study area (downstream of Wadi Hanifa in the South of Al Riyadh, Wadi Al Kharj in the South of Al Kharj City and some of the wells in the rural areas) must be considered. Whenever wastewater moves through the soil and rock into the shallow aquifer, it is subjected to flow through the unsaturated and saturated zones. Contamination travels primarily through the thin layers of soil at the surface of saturated zone. An assessment of the quality of groundwater, hydrochemical and bacteriological assessment of groundwater sampled from Abeokuta (Nigeria) and its environ, have been presented by Aladejana and Talabi (2013 [10]). The results have demonstrated that the shallow wells water in Abeokuta were suitable for irrigation purpose but not potable and need to be treated to remove the possible bacterial pollution before consumption.

Study area : Al Kharj city is located in the south of Al Riyadh city which is located in the central region of Saudi Arabia. It is around 40 km2 in area in which more settlements are being developed, even on the flood-prone areas (Fig. 1). It is lying between UTM coordinates Easting 690000 and 740000 and Northing 2660000 and 2720000. The high consumption of quantities of water for drinking, everyday uses like washing and industrial use has been noted and the trend will continue to increase into the future. For this reason, the Ministry of Electricity and Water of Saudi Arabia has created a department dealing with groundwater from the investigation phase to the controlling and monitoring of troughs and shallow wells. The Ministry has made efforts in the exploitation and management of groundwater in order to provide for the growing needs of water especially in Al Kharj area and giving more importance to new tools in Civil Engineering, based on computer sciences such as GIS application and modeling. Figure 2 shows the Digital Elevation Model (DEM) of the study area lying between latitudes N 22°30′00″ and N 24°45′00″ and longitudes E 45°45′00″ and E 47°15′00″ which is used to model the runoff in the major wadis and tributaries based on ArcHydro program implemented within ArcGIS10 software.

Fig. 1. Image satellite of Al Kharj area (RSI-KACST, 2013).

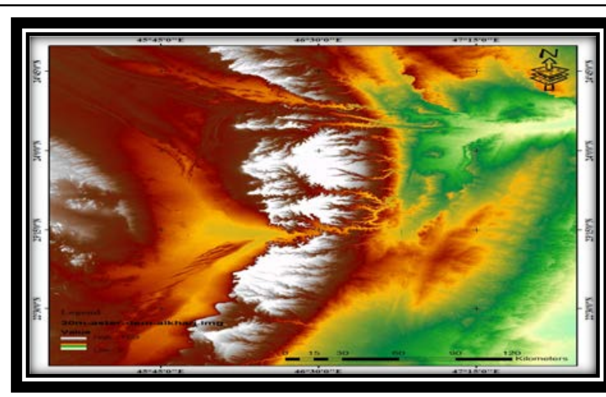

Fig. 2. Digital Elevation Model of Al Kharj area (RSI-KACST,

2 MATERIELS AND METHODS

Some steps were taken to complete this study. In the first step, according to the study area and the network of wadis within the watershed of AlKharj area and their important role in recharging the aquifer and importantly, multiple

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inflows and outflows streams from the aquifer, the network has been considered as a big area. Some data such as topography from (DEM), statistics of the water level in piezometers, maps of potability, map of the shallow aquifer bed rock, discharge rate of the plain wells, and so on were studied and confirmed and were applied to the flow model. Topography of ground surface was transferred to the model using topography maps with scale of 1/50000 (to depict the bedrock and other features). In the study area, the highest and lowest parts are located in the South-West and North-East respectively. By having bedrock topography map and using ArcGIS Desktop software, the thickness of each cell/grid of the study was derived. Mean of observed water tables in a sets of wells (due to its minimum fluctuations) was considered and applied as initial hydraulic head in the stream model in steady condition. Potability and hydraulic conductivity values of the aquifer were measured to calibrate the ModFlow model. Calculation of underground inflows was carried out using potability and Darcy equation. According to the statistics of the Ministry of Electricity and Water, there are a lot of wells which yield some million m^3 of groundwater resources per year since 1988 in the study area. Water table of the central zone in the study area was determined using existing statistics. The recharge of the wadis sediments layers was calculated and applied to the ModFlow model by using conductance coefficient (C). Stream model calibration in the study area was conducted using observed and simulated water table. After transporting data, the stream model was performed and then the model was calibrated using the results (simulated water table). Among input data of the model, hydraulic conductivity and specific flow have the highest importance and sensitivity in model calibration. The desired result was achieved after 20 implementations of flow model. The fig. 10 shows the location of observation wells in the central zone of the study area of AlKharj. In the second step, using Geographic Information Systems, data and information required from hydro-geological point of view are complex. Information concerning geology, hydrology, geo-morphology, soil, climate, land use, land cover, topography, and urban planning features needs to be analyzed and combined. Data are collected from existing databases and maps as well as through field measurements. Point (manual and automatic) collecting systems for some of the physical and chemical parameters are being increasingly used based on GPS Garmin and remote-sensing techniques to assess parameters related to soil, the unsaturated zone, geo-morphology, climate and hydrology. All these data need to be managed, and this can be achieved using spatial databases, particularly GIS databases. Storing data implies data analysis, conceptual design of data models, and data representation. In hydrogeology, because of a limited number of sample locations, point attribute data also need to be processed by applying adequate kinds of interpolation or modeling algorithms. The derived data also need to be managed. In the third step, ModFlow model was used to assess and model groundwater flow. This model was produced by McDonald and Harbaugh [11] using Fortran 77 programming language. Programming structure of this software is modular which allows one to adjust data entry and exit of the program and data exchange between its various parts. Also, the modular structure makes it possible to develop the software significantly so that, since 1998 to date, this program has been evolving constantly. For this study, we used the 2005 version [12] which has many options for exchanging files with ArcGIS10 software.

3 Results and Discussions

The study area is underlined by limestone rocks strata layers, fluvio-alluvium sediments formation and sandstone and clay rocks occupy and isolated hills. The central part of the study area is occupied by a network of wadis with sediments and sand dunes as shown in Figure 14. Other rock types are present in a smaller portion of the study area. The limestone rock masses are highly weathered, jointed and fractured. There are joints and fractures connected with underground cavities called "karsts" especially at the West of AlKarj city, and there weathered and fractured zones, which forms potential groundwater zones besides the main water table along the main wadis in the central area of AlKharj area watershed (Figure 1). According to the Digital Elevation Model (Figure 2), the morphology of the study area allows depicting of the effect of the interconnection of all the wadis in this area especially in the central one where a consistent groundwater capacity has been indexed. The geomorphological units are highly helpful for selecting the artificial recharge sites at the West of selected water table near the surface. In the present investigation, the classification of various landforms based on geomorphology, such as buried pediment shallow, sedimentary plain was achieved and the groundwater potential zones were demarcated (Figure 9). These landforms act as groundwater storage reservoirs and some of them act as recharge and run-off zones (Figure 3). The shallow buried pediments cover the largest portion of the study area. The land use/land cover of the study area is characterized essentially by palm trees for date production and other irrigated agricultural activities based on the groundwater represented by a set of shallow wells. These are readily interpretable from the satellite images (Figure 8). The detailed land use/land cover spatial distribution is depicted in the fig.10. The annual average water level spatial distribution map reveals that a major portion of the study area is covered by shallow depth of

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water level (water table) between 30 and 120 m where more than 30% of water has been used in AlKharj city and for irrigated agricultural activities.

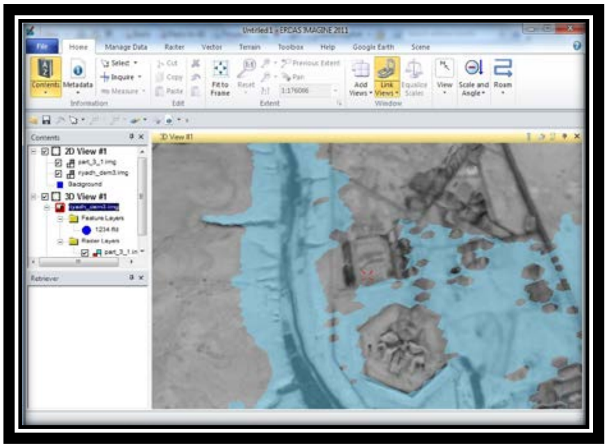

Fig. 3. Flood simulation using Erdas2001 according to 100 years return period (Kheder K., 2013 [13])

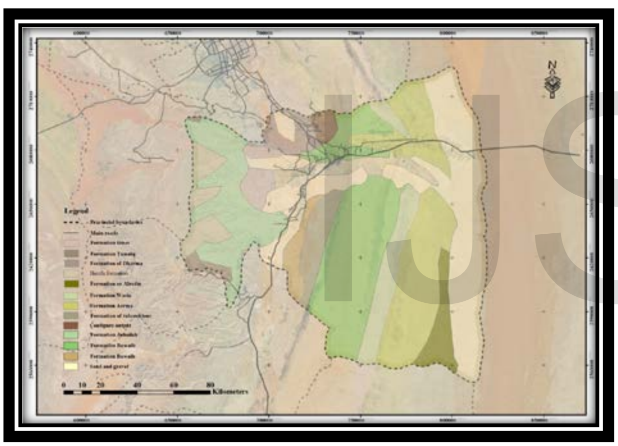

Fig. 4. Main geological structures in Al Kharj area.

Fig. 5. Main land cover layers in Al Kharj area.

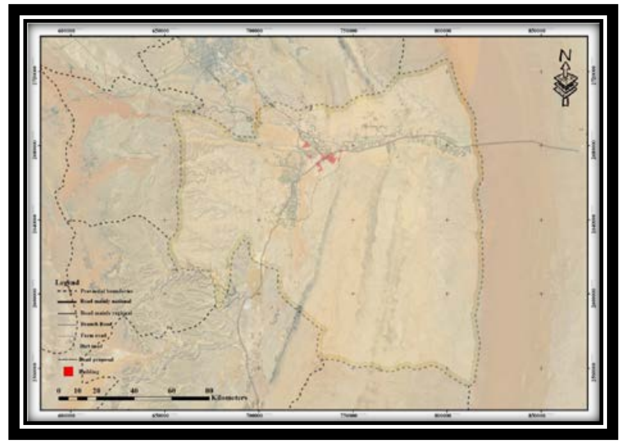

Fig. 6. Urban area in Al Kharj area.

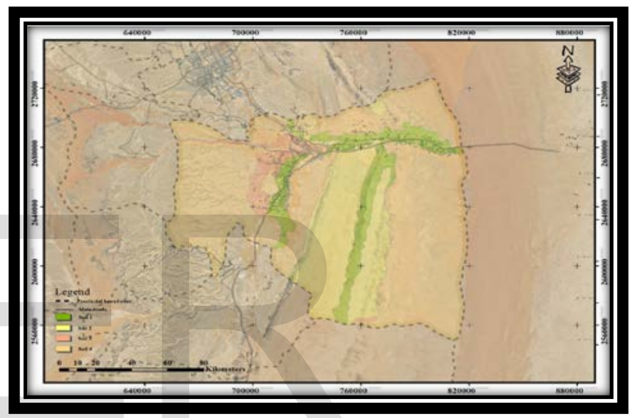

Fig. 7. Main soil layers in Al Kharj area.

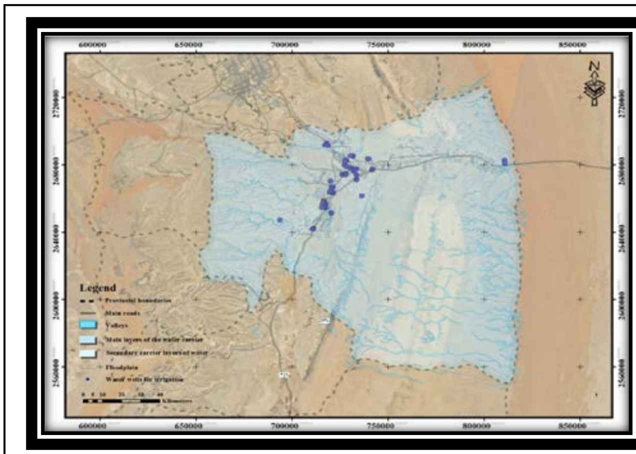

Fig. 8. Main shallow wells in Al Kharj area.

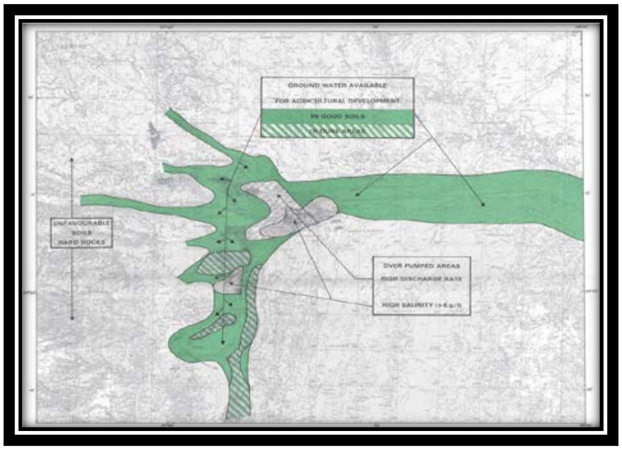

Fig. 9. Groundwater availability in Al Kharj area.

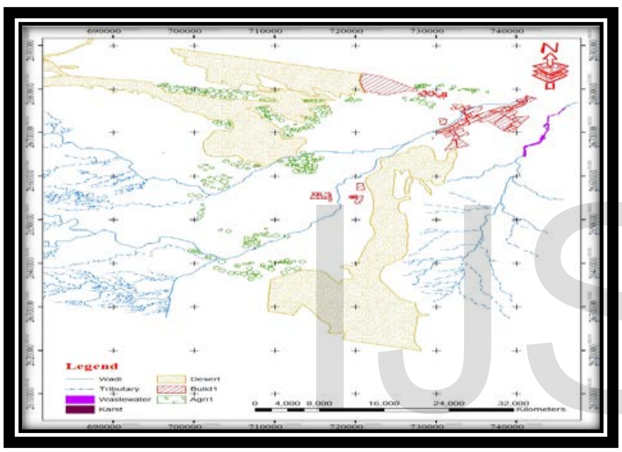

Fig. 10. Main updated layers in Al Kharj area.

4 Conclusions and Recommendations

The groundwater recharge of the central area of AlKharj watershed is the result of an interaction between geo-morphology and water level in the process of permanent adjustment between constraining properties. The present integrated study has made the following conclusions. Geologically, it is observed that the groundwater is mainly confined to secondary porosity i.e. fractured zone, fault, joint and weathered column. It is observed from field survey and also from various wells located in the central area where groundwater flows from the West to the East. Based on Geographic Information Systems and ModFlow modeling, it is possible to estimate the balance of groundwater resource and distribution of groundwater. From the generated ground water resource prospect map, it is observed that high potential zones are mainly located along lineaments and in pediment areas. Alluvial fills, valley fills are good potential zones. The bedside area in which many underground cavities called "karsts" can be useful as good groundwater prospective zones. As a recommendation; based on the increasing volume of wastewater from the North West and South East of the study area, and by using GPS to quantify the water table and water quality in many shallow wells in this region, the next step of this research could involve a more rigorous analysis for pollution forecasting, planning and management.

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