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MANAGEMENT OF BAI HASSAN UNCONFINED AQUIFER, LESSER ZAB RIVER BASIN, KURDISTAN REGION, IRAQ USING A MODELING APPROACH

[1]Moutaz A. Al-Dabbas, [2]David K. Kreamer*, [3]Ayad A. Al-Shammari and [3]Ali M. Jwad
[1]College of Science, University of Baghdad, Baghdad, Iraq
[2]Department of Geoscience, University of Nevada, Las Vegas, USA
[3]Water Management Research Centre, Ministry of Water Resources, Baghdad, Iraq
*Email: dave.kreamer@unlv.edu

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ABSTRACT

A numerical groundwater modeling approach is presented to quantify spatial and temporal trends in groundwater flow and availability, and to analyze the cumulative impacts of human activity on the shallow Bai Hassan aquifer underlying the central portion of the Lesser Zab River Basin, Kurdistan region, Iraq. The study area lies in the Kurdistan region of northeastern Iraq between the cities of Mosul, Kirkuk, Erbil, and Dokan. Increasing population, some of which has been displaced by conflict, coupled with continuing drought, climate change, and increasing agricultural irrigation, has intensified the need to identify water resources in the region. The Bai Hassan Formation (Pliocene – Pleistocene) is exposed in much of the basin and appears as a large potential source of water. Initial model inputs are in part based on the 365 historical data from the Iraqi Ministry of Water Resources and monitoring of about 40 wells in the area during 2014. The transient simulation model assumes 500 new wells will be drilled within the next ten years, with a discharge rate equal to 20 l/sec and with a pumping duration of eight hours daily. Simulations model of the future pumping and recharge for five and ten years from the present shows a general decrease in hydraulic head in the unconfined aquifer on both sides of the Lesser Zab River but do not show significant and immediate impact on the surface water flow. The recommended solution is to prevent excessive depletion in the middle and southern parts.

Keywords: Groundwater management; Numerical modeling; Water supply; Bai Hassan; aquifer; Iraq

INTRODUCTION

Water is a critical part of resources management in the Middle East and Iraq in particular. The region has suffered war, shifting and expanding populations including refugees, natural disasters, higher demands for municipal water use and drinking water, and increasing water use for irrigated agriculture which supplements rain-fed farming (Awadh and Al-Kilabi, 2016). Much of the water has traditionally been supplied by surface water flows such as the Tigris and Euphrates rivers. The Tigris River Basin in particular has several important tributary sub-basins that flow into Iraq from Turkey and Iran. The main contributors to Tigris discharge are the Greater and Lesser Zab Rivers and represent 40-60% of the Tigris flow that reaches Baghdad (Fig. 1).

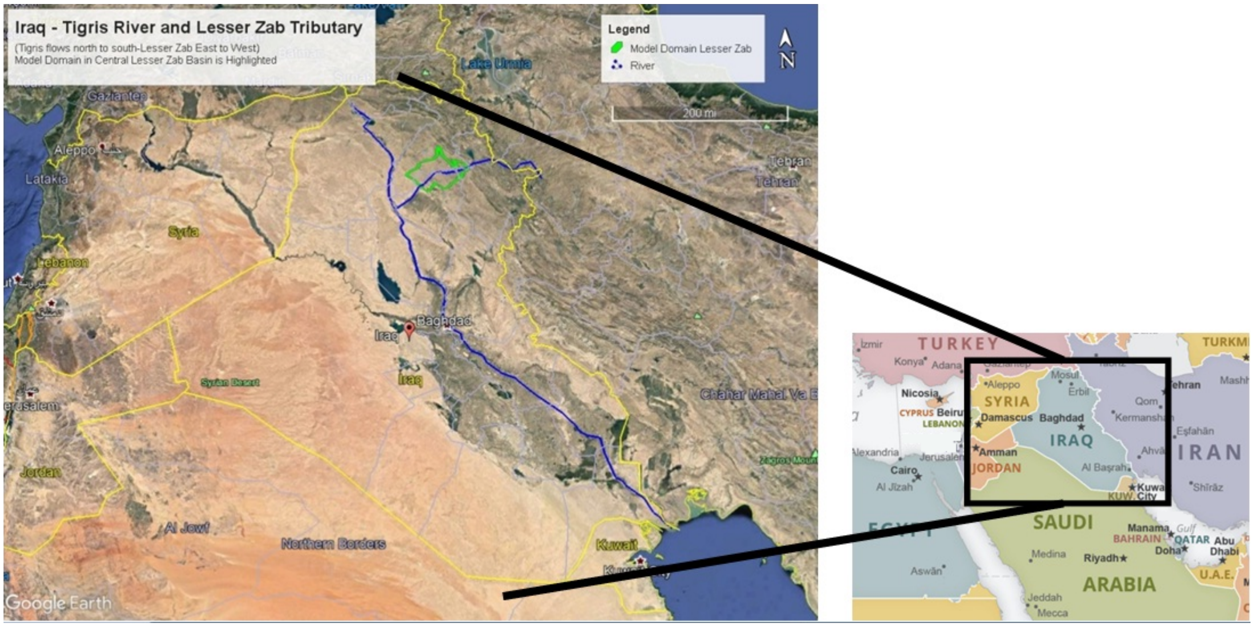


Fig. 1. Tigris and Lesser Zab rivers in Iraq, the middle portion of the Lesser Zab basin indicated in green (Modified from Google Earth)

These tributaries significantly contribute to total Tigris River volume and discharge, which is essential to many Iraqi cities, including Baghdad, and much of the irrigated agriculture throughout the country (Al-Hamdani et al., 2016b). The surface water has always been important through the centuries, groundwater in these river basins and their sub-basins has seen growing exploitation, particularly in recent years (Al-Hamdani et al., 2016a). The Lesser Zab River Basin is located between longitudes (43° 21′ 41" – 46º 17′ 55") E, and latitudes (35° 1′ 29" – 36º 54′ 41") N, (Figs. 2 and 3). Its areal extent is about 21,475 km^2 which represents about 6.5 % of the Tigris River Basin and it is drained initially from southeast and northwest beginning in the

Zagros Mountains (about 3,000 m a.s.l.), where it follows the alignment of the axis of these mountain chains. The river flow changes to a westward flow through several gorges and enters the lower folded zone, which is considered the central region of the Lesser Zab Basin and is the focus of this study (FAO, 2017). Other important pressures on resources, particularly those that increase water scarcity, are recent prolonged droughts over two decades, reduced precipitation, and high summer temperatures associated with climate change (Azooz and Talal, 2015).

The middle section of the Lesser Zab River Basin, between the cities of Mosul, Kirkuk, Erbil, and Dokan, is underlain by the unconfined aquifer of Bai Hassan Formation which has experienced increased use in recent years, some of which is due to agricultural development (Awadh et al., 2015; Al-Hamdani et al., 2016b). One of the reasons groundwater in the central section of the Lesser Zab Basin plays an important role in agricultural and municipal activities is that most villages far from the river regularly use groundwater for drinking and other consumptive uses. Consequently, the Bai Hassan aquifer system is an essential feature and important resource for the area (Awadh and Al-Kilabi, 2016; Al-Hamdani et al., 2016a; and Al-Hamdani et al., 2016b). Drought has impacted groundwater wells, drying up with lowering water tables. Voss et al (2013) showed alarming groundwater decreases in the Tigris and Euphrates river basins. Future estimates are that Iraqi water supplies will continue to decline (Abbas et al., 2016), and demands will regularly exceed those supplies (Al-Ansari et al., 2019). Jirjees et al., (2020) mentioned that the values of the rainfall of winter and spring are the most effective for creation of discharge. Surface runoff is about % 30.4 of the rainfall and groundwater recharge is about % 26.2 of the rainfall. Iran has intensified diversion of water in the headwaters of the Lesser Zab river with some estimates of an 80% drop in the river's water level in Iraq. Iran has been building and has plans to build many dams which will divert water flowing into Iraq in the future. The construction of Kolsa dam in the Sardasht region of Iran has reduced the flow of the Lesser Zab, impacted crop production, increased river salinity, and amplified concerns about future drought conditions (Awadh and Al-Kilabi, 2016). The Bai Hassan aquifer system is an essential feature and an important resource for the area. Many researchers have studied and evaluated the groundwater resources in Lesser Zab River basin such as Jawad (2010); Al-Jiburi, and Al-Basrawi (2012); Swlri (2014); Mulder et al (2015) and (Ashri-2) 2018. But these studies do not deal with broad scale modeling and prediction of the future utilization of groundwater and the impacts of continuing and increasing groundwater withdrawal. Aziz et al. (2020) studied the

Diyala river basin by using the flow accumulation layer in the contributing a watershed. The sub-basins were delineated by pour point to computing the flow direction and using it in the watershed function. As a result, five sub-basins have been delineated in the study area. The objectives of this study are to quantify spatial and temporal trends in groundwater flow and availability for the central portion of the Lesser Zab Basin, specifically in the unconfined aquifer associated with the Bai Hassan Formation, and to analyze the cumulative impacts of human activity on this resource. A rudimentary numerical groundwater model was constructed to simulate groundwater recharge, discharge, and flow, impacts of increased pumping and groundwater withdrawal 5 to 10 years into the future.

STUDY AREA

The focus of this study is the middle section of Lesser Zab Basin where some intermittent streams from small tributaries and sub-basins join the river, passing through what is geologically referred to as the Lower Folded Zone. These sub-basins are the Alton Copri, Daibaga, Bai Hassan and South Erbil and Qardaso that enter the Lesser Zab River, which in turn joins the Tigris (Fig. 2). Geologically, the lower folded zone has exposed strata ranging from the Shiranish Formation of the Late Cretaceous to the Bai Hassan Formation of Pliocene-Pleistocene age (Jassim and Buday, 2006). The overlying, youngest, Pliocene-Pleistocene molasse sediments were deposited in a subsiding foredeep basin. These youngest sediments are the dominant strata exposed in the middle section of the Lesser Zab River, which is the location of this study's groundwater modeling domain (Fig. 3). The primarily exposed formations are the Mukdadiyak and the Bai Hassan, with the main, shallow, unconfined aquifer of the Bai Hassan Formation selected to represent the aquifers in the study area that are mainly recharged from the rainwater. The Bai Hassan Formation (Pliocene – Pleistocene) has alternating conglomerate and pebbly sandstone beds (Jassim and Buday, 2006). These beds are of variable thickness and exposed in the middle part of the basin. Additional Quaternary sediments are exposed in a relatively small area, generally having less than 25 m thickness.

The main shallow aquifer in the basin extends within the Bai Hassan Formation sediments, and represents a large potential source of water in the study area (Abbas et al., 2016). The aquifer is recharged mainly from rainfall and, due to the reduction of precipitation and increasing temperatures with time, the amount of recharge is also declining (Voss et al., 2013 and Abbas et al., 2016). Groundwater electrical conductivity typically increases from northeast to southwest in this portion of the low folded zone and transitions from bicarbonate-type water to sulphatic from recharge to discharge areas (Al-Jiburi and Al-Basrawi, 2012). The sub-basins of the central Lesser Zab River vary considerably in the groundwater quality, for example in Alton Copri Province being mostly freshwater, while increasing brackish water in the Daibaga Province (Ashri-2, 2018).

Groundwater in this layer is replenished from an average annual rainfall of approximately 400mm through gravels in dendritically-shaped valleys (Al-Shammari, 2015). The climate of the middle Lesser Zab Basin is characterized by wet winters and dry summers. Rainfall is the lowest in the western and southern parts of the Lesser Zab Basin.

MATERIALS AND METHODS

Data from 365 wells (unconfined aquifer) from the hydrogeological database of Iraqi Ministry of Water Resources (MoWR), in addition to 40 wells (mostly for irrigation) that had been checked during 2014 field visits, were used to determine the hydraulic heads of the aquifers in the Iraqi side of the Zab River Basin (Fig.3). According to (Swlri, 2014) and (Al-Shammari, 2015) the available data of hydraulic heads, considered a reliable database of 405 unconfined wells in the Lesser Zab River Basin, were used to prepare contour maps that indicate the general direction of groundwater movement within the aquifer (Fig. 4).

Groundwater generally flows to the southwest, and low gradients are associated with areas of highly permeable sand and gravel of the Quaternary sediments and the Bai Hassan Formation. Flow patterns in the upper areas of the low folded zone unconfined aquifer indicate that groundwater is the main replenishing source of the Lesser Zab River. Forty wells were surveyed monthly during 2014 (Fig.3). The average observed water table of the Bai Hassan aquifer wells are indicated in Table 1. Determined hydraulic gradients which, in conjunction with the hydraulic properties of the aquifer, were used to estimate the groundwater flow velocities and support groundwater model development. Twelve groundwater wells (from the surveyed 40 wells) were not applied to the groundwater flow model, but were used for model verification (Table 2).

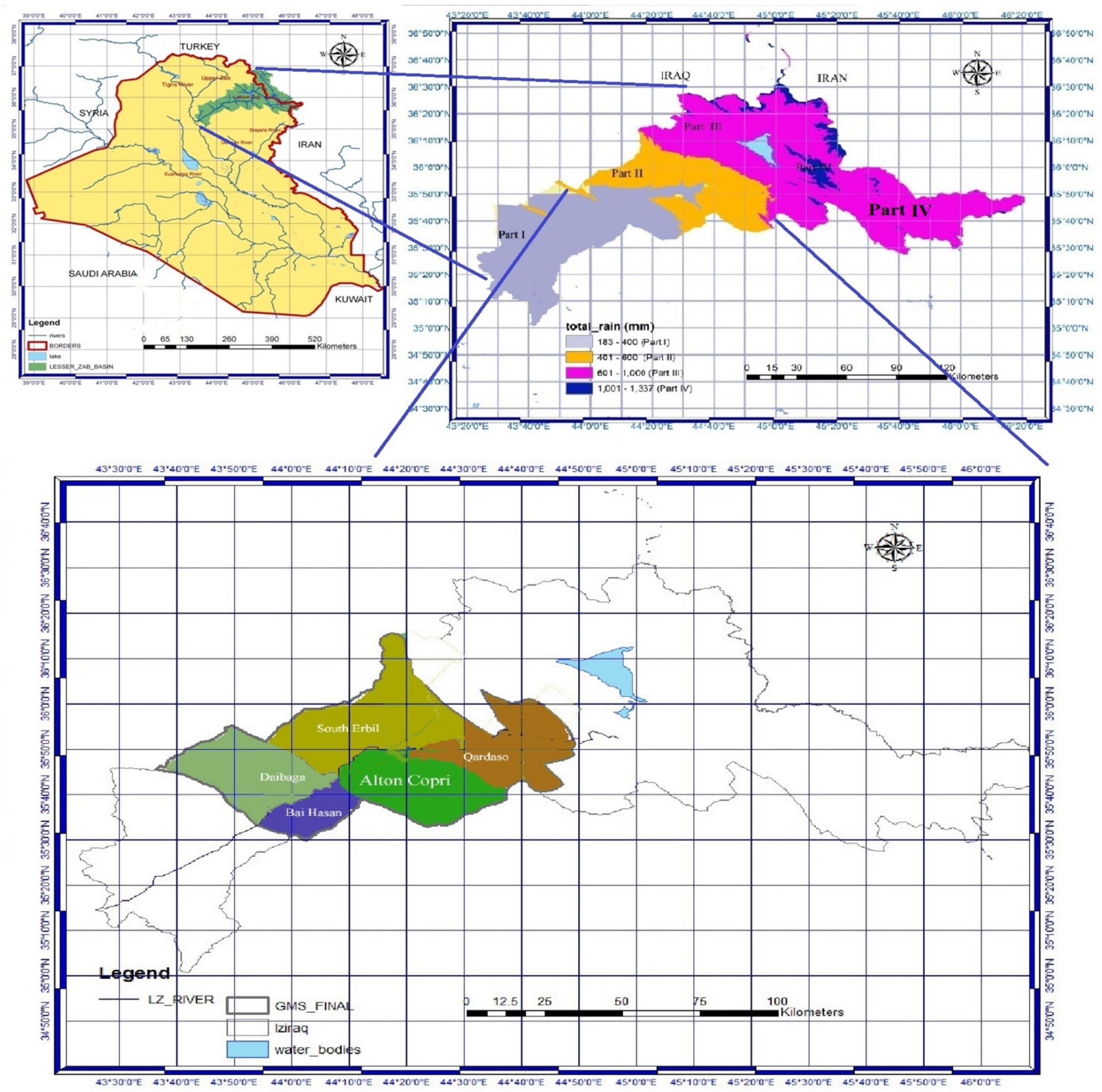


Fig. 2. Location of the study area in the middle Lesser Zab Basin shows increasing of precipitation in the eastern part of the basin, and the five sub-basins of the modeled region (modified after Jawad, 2010)

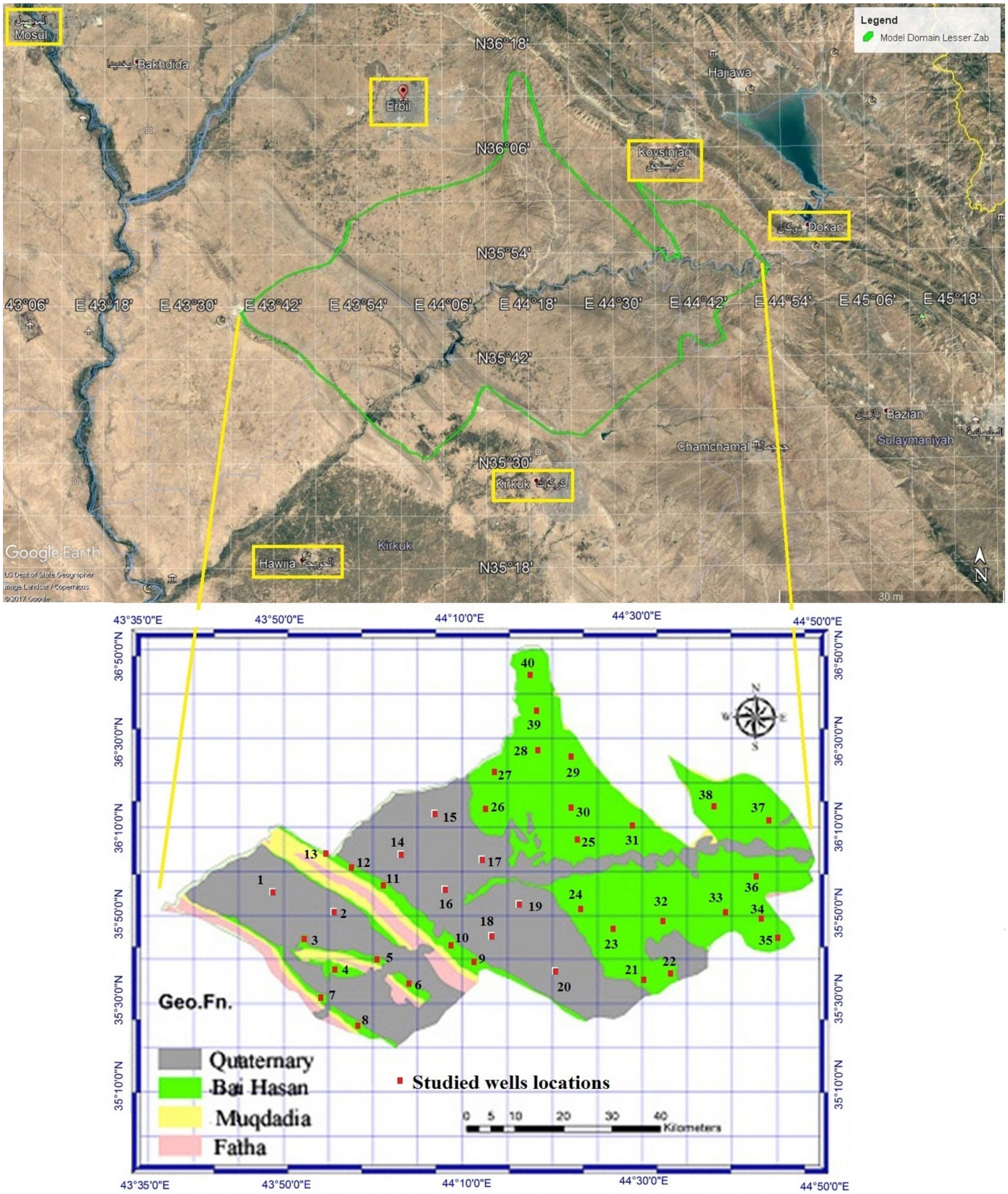


Fig. 3. Geological map with the groundwater wells locations of the Lesser Zab River Basin (Al-Shammari, 2015)

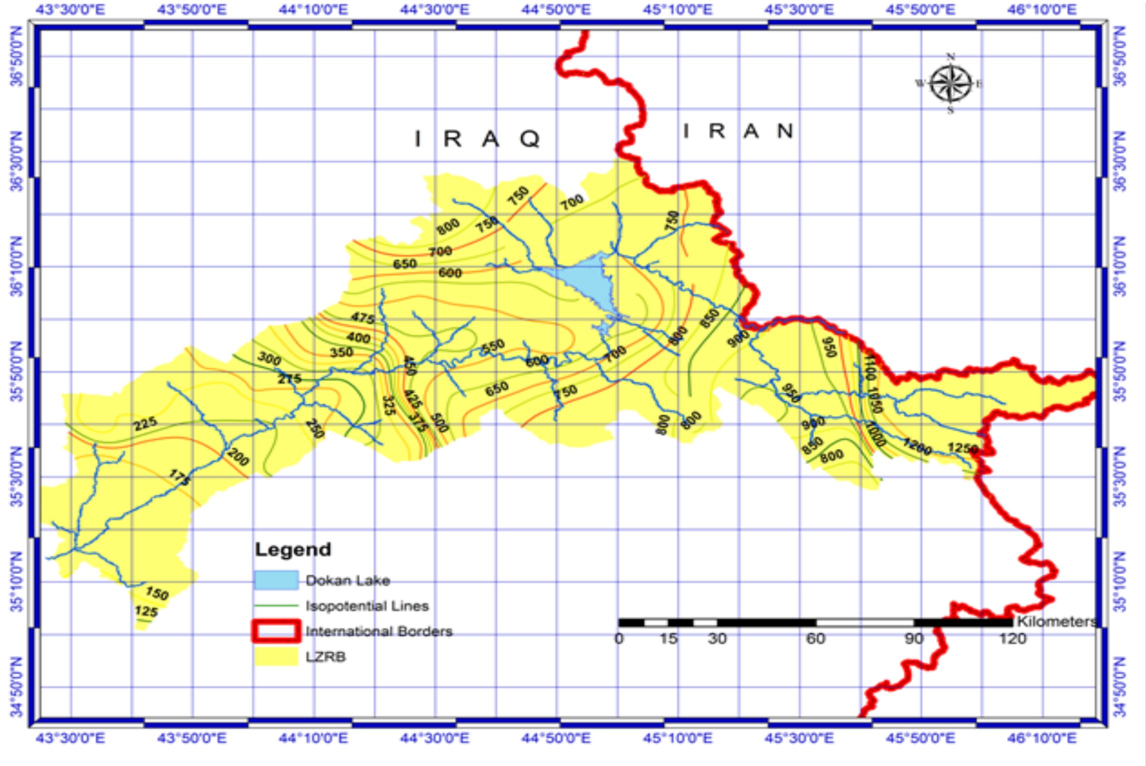


Fig. 4. Regional flow direction of groundwater in an unconfined aquifer (After Swlri, 2014 and Al-Shammari, 2015)

Estimation of Natural Groundwater Recharge

Empirical formulae showing rainfall -recharge relationship was selected for the estimation of recharge based on the modified work of Krishna Rao (Kumar, 2009). The formula was selected because there is a wide difference in rainfall range and the availability of many climatologic stations. Krishna Rao gave the following relationship to determine the groundwater recharge:

$R_r = K (P - X)$ (1)

Where:

R_r = Groundwater recharge (mm).

P = Mean annual rainfall in (mm).

K = Constant

X = Precipitation Value in (mm)

Table 1. The average observed water table (m.a.s.l.) during 2014 of the Bai Hassan aquifer wells (Al-Shammari, 2015)

Well No.	Observed water table	Well No.	Observed water table	Well No.	Observed water table	Well No.	Observed water table
1	198	11	271	21	378	31	452
2	223	12	282	22	493	32	476
3	199	13	259	23	374	33	547
4	207	14	291	24	326	34	629
5	211	15	312	25	353	35	671
6	194	16	304	26	341	36	606
7	187	17	342	27	376	37	262
8	186	18	287	28	411	38	253
9	243	19	317	29	443	39	683
10	254	20	297	30	423	40	697

According to Rao, the following relationships hold for different annual rainfall conditions:

$R_r = 0.20 (P - 400)$ for areas with annual normal rainfall (P) between 400 and 600 mm.

$R_r = 0.25 (P - 400)$ for areas with P between 600 and 1000 mm.

$R_r = 0.35 (P - 600)$ for areas with P above 1000 mm.

As a heuristic example for the Lesser Zab, a recharge value can be calculated for the area which is situated between isohyet lines (400-600) mm/ year (part II), which represents a majority of the modeling domain. The mean value of annual rainfall over the entire basin was (477.36) mm (Fig. 5). The depth of effective precipitation available for recharge would be calculated, according to the Rao formula (Kumar, 2009):

$R_r = 0.20 (P - 400)$

$R_r = 0.20(477.363-400)$

$R_r = 15.4726$ mm/yr

Using the average recharge and recharge area, the annual volume of recharge ($m^{3)}$ is calculated:

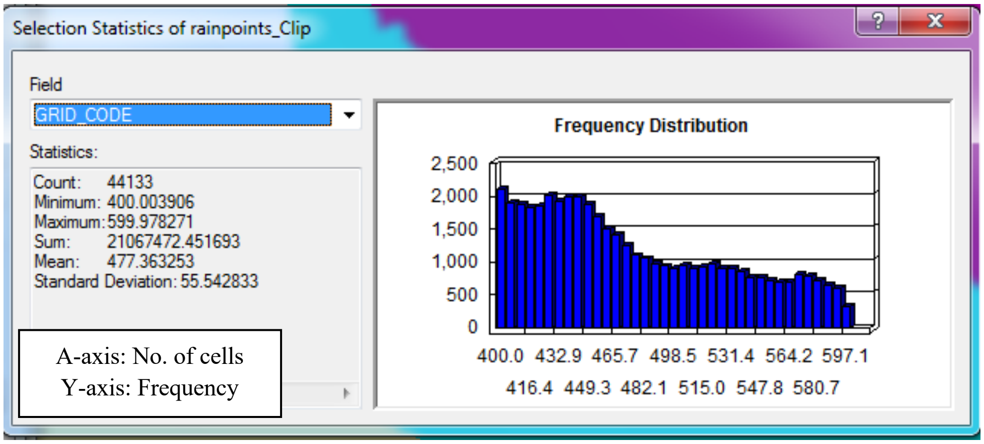
$R_{total} = ((15.47 \text{mm/yr}) * 0.001 \text{m/mm}) * \text{Area m}^2$

Area = Number of active cells * cell area

Area = $1372*2{,}160{,}000 \text{ m}^2$

$R_{total} = (0.01547 \text{m/yr}) *2{,}963{,}520{,}000 \text{ m}^2$

$R_{total} = 45{,}851{,}580 \text{ m}^3$ / year.



Selection Statistics of rainpoints_Clip

Field: GRID_CODE

Statistics:

Count: 44133
Minimum: 400.003906
Maximum: 599.978271
Sum: 21067472.451693
Mean: 477.363253
Standard Deviation: 55.542833

A-axis: No. of cells
Y-axis: Frequency

Fig. 5. Statistics of mean rainfall in (part II) (After Al-Shammari, 2015)

Aquifer Characteristics

The understanding of the aquifer hydraulic characteristics is a key piece of managing an aquifer efficiently. The modeled area is formed from five catchments of about 2963.5 km^2, Altun Copri, Daibaga, Bai Hassan, South Erbil, and Qardaso catchments (Fig. 2). An aquifer (pumping) test is regarded as the best way to acquire these characteristics. According to Al-Shammari (2015), the wells are known to have variable but in general, high yields 20 - 30 l/sec (with some exception), values of the coefficient transmissivity found a range between 90 to 2994 m^2 /day, and the specific yield ranges between 5.0 x 10^{-3} to 1.8 x 10^{-2}.

Groundwater Modeling System (GMS) Software

Groundwater Modeling System v.10.4 (GMS) preprocessing software, Aquaveo (2018) was applied with GIS to aid in graphically representing the region of interest and to help generate, manage, and apply a basic conceptual model design to the Bai Hassan aquifer. GMS uses the finite-difference, numerical groundwater model MODFLOW, McDonald and Harbaugh (1988) with input from GIS-based objects which have been identified as influencing the overall regional water balance. In particular, these utilities were used to demarcate recharge zones and create a database that defined the spatial distribution and calculated inputs for groundwater recharge.

Modeling Considerations

The goals of numerical groundwater modeling can provide a basis for prediction of future water resource use, pumping test scenarios, warn of over-exploitation and water table decline, and aid in resource management decisions (Voss et al., 2013). The aim of this study is to model and estimate the hydraulic head distribution and variation in the unconfined aquifer under steady-state and transient-state conditions. The initial and boundaries are measured and entered as input data in the model. The modeled area was chosen to represent the upper water bearing layer and was formed from five watersheds (Figs. 2 and 3) which represent side drainages to the middle reach of the Lesser Zab River. Groundwater Modeling System v.10.4 (GMS) Software was applied with GIS to aid in representing the region of interest and to help generate, manage, and apply a basic conceptual model design to the aquifer (Aquaveo, 2018). The water balance of the aquifer system in this basin and in many arid regions is strongly influenced by local precipitation and resultant recharge (Mall et al., 2006). This is particularly the case in the more arid and water stressed regions of the Lesser Zab Basin. Rainfall is believed to be the principal source for soil-water replenishment and recharge of groundwater in the middle portion of the Lesser Zab basin (IOM, 2000; NOAA, 2018). Accordingly, Part II rainfall is ranging between 400-600 mm (Figs.2 and 5). The potential evapotranspiration (PET) in the basin is approximately 1400-1600 mm/year (Al-Shammari, 2015; De Pauw et al., 2015). In the less arid parts of the basin of Part II, the modified Chaturvedi and Krishna Rao formulas were utilized to estimate PET, empirical formulae showing the rainfall -recharge relationship were selected for the estimation of recharge (Kumar, 2009; FAO, 2009; Abbasa et al., 2016). Fluctuation in groundwater hydraulic head with less than average rainfall and recharge can be numerically modeled to simulate response to periods of stress.

Model Description

For conceptual and management purposes, a numerical groundwater flow model was developed for the Bai Hassan Formation as part of a Lesser Zab River Basin. The model was based on the 3-D finite difference based MODFLOW, groundwater recharge amounts and the demarcation and spatial distribution of recharge zones were delineated using a Geographical Information System (GIS), similar to Singhal and Goyal (2011). The model domain for the Bai Hassan Formation is shown in Fig. 6. The model is discretized into a grid of cells and groundwater flow equations are then solved to describe groundwater flow between adjacent model cells. The grid is oriented azimuthally north-south, east-west, and is composed of 62 columns and 68 rows. The cell dimensions are 1600m x 1350m. This grid set up extends beyond the basin boundaries and the total number of active cells is 1372, representing a watershed area of 2963.5 km^2 within the 4328 km^2 area of the central Lesser Zab Basin. The selection of the rectangular grid orientation, number of cells, and cell dimensions is based on the areal extent of the modeled system, computer run times, data density, and the nature of the problem being addressed - representation of steady state and temporal water table fluctuation in the aquifer (Wylie, 2004). The nodes on the grid are regularly spaced, not expanded toward regional boundaries, and generally both grid orientation and domain boundaries are parallel/perpendicular to expected groundwater flow as recommended by Aquaterra (2018). The grid size selection for the Lesser Zab Basin was a compromise between the need for this sub-regional model to cover a smaller area with finer cell size and the need to address larger, more general issues associated with regional modeling on a large scale (Wylie, 2004).

Aquifer Properties of the Modeled Area

MODFLOW input requires additional physical properties of the unconfined aquifer, for instance, top and bottom of the aquifer, in addition to hydraulic properties such as transmissivity, hydraulic head, and specific yield (Figs. 7 and 8). These values were loaded into the model, similar to the approach in Singhal and Goyal (2011). The input data for the unconfined Bai Hassan aquifer is based on historical data of 365 and the monitoring of 40 wells during 2014, and are assigned to the model grid as initial hydraulic heads and transmissivities for steady state simulation, and additionally specific yield for transient state modeling. Inactive cells within the domain of the middle reach of the Lesser Zab are typically those cells were there are no nearby wells or groundwater exploitation, and little expected contribution to recharge. Constant head values are assigned to cells along the Lesser Zab River, according to average river stage.

Steady-State Simulation

A steady-state model was run for the middle reach of the Lesser Zab Basin in advance of time-dependent modeling of groundwater flow. Steady flow (time invariant) groundwater simulation constrains the volumetric flux passing any given point to a constant value with time. An initial, time invariant condition is often a good starting point for further transient-state groundwater modeling. Average recharge values were input as a function of long-term precipitation. Typical groundwater extraction rates, as well as initial estimates of the hydrologic properties of the domain were also input. After loading data and running the model, computer-generated hydraulic heads are the primary results of MODFLOW as the time invariant simulation (Fig. 9).

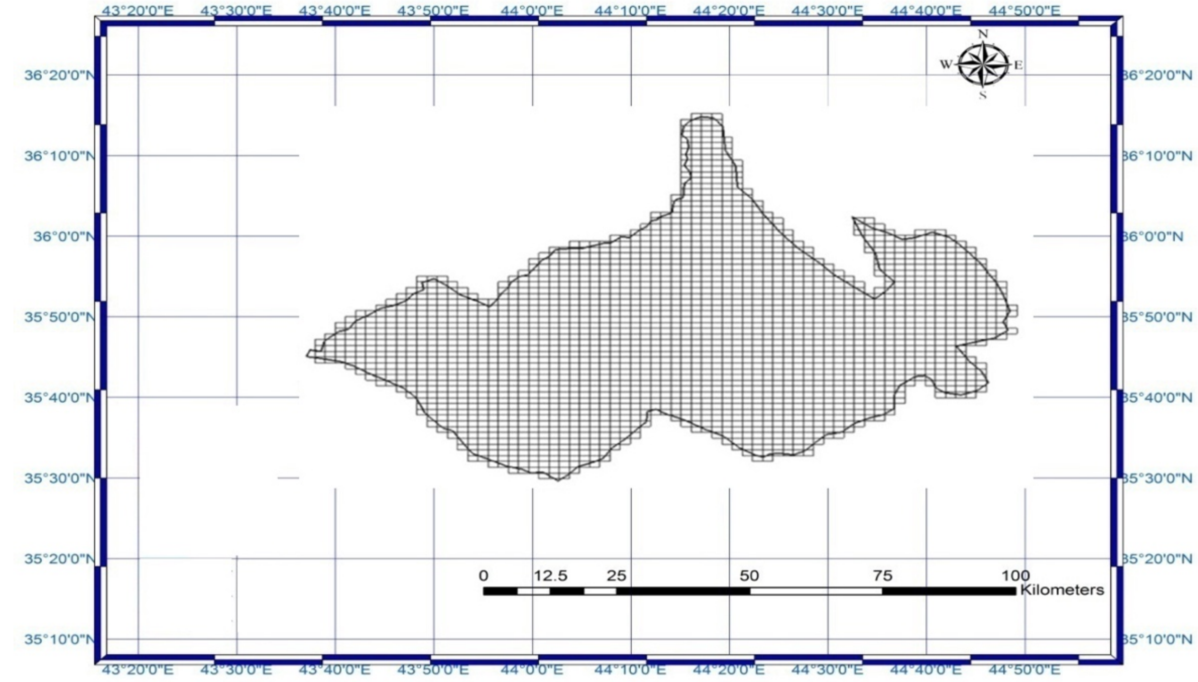


Fig. 6. Grid of the modeled area

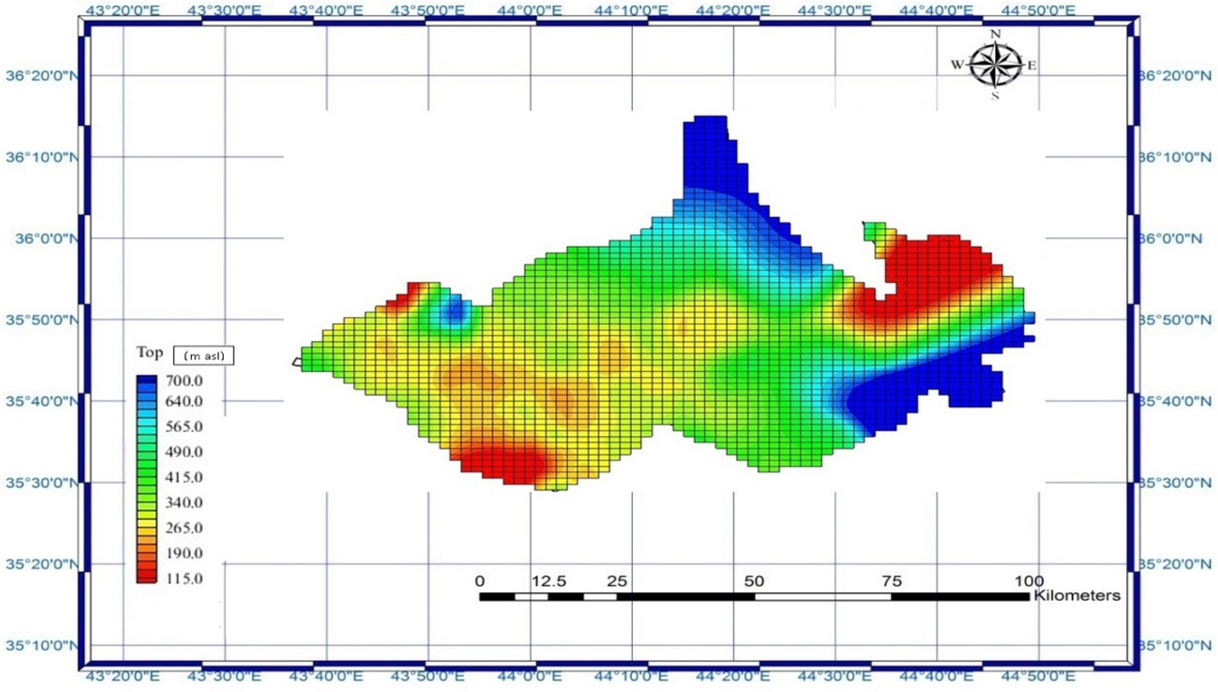


Fig. 7. Top of the unconfined aquifers

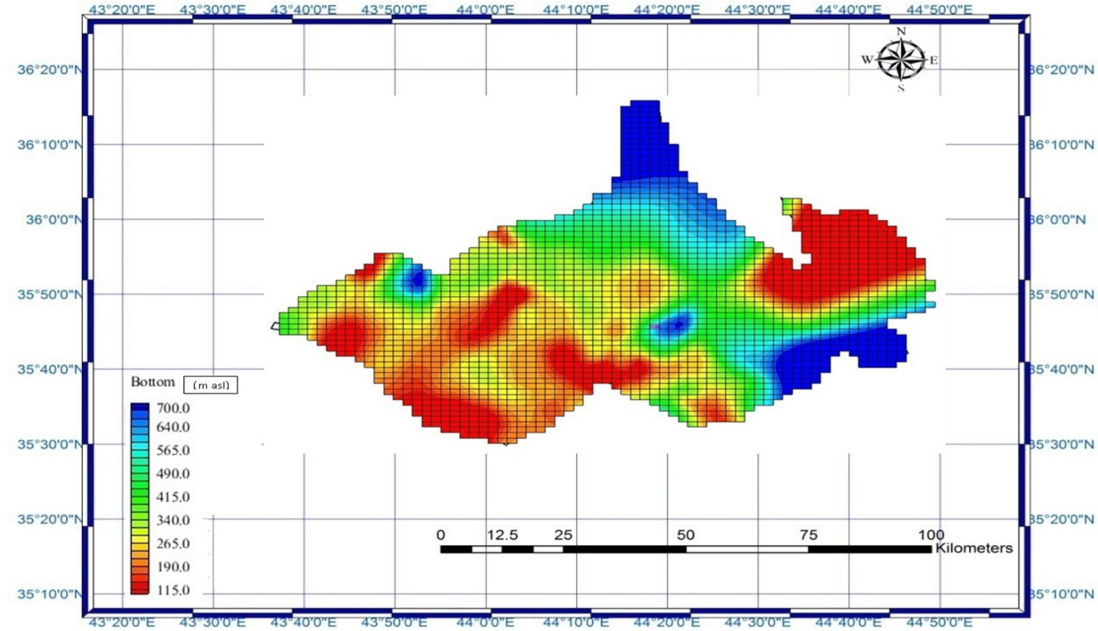


Fig. 8. Bottom of the unconfined aquifers

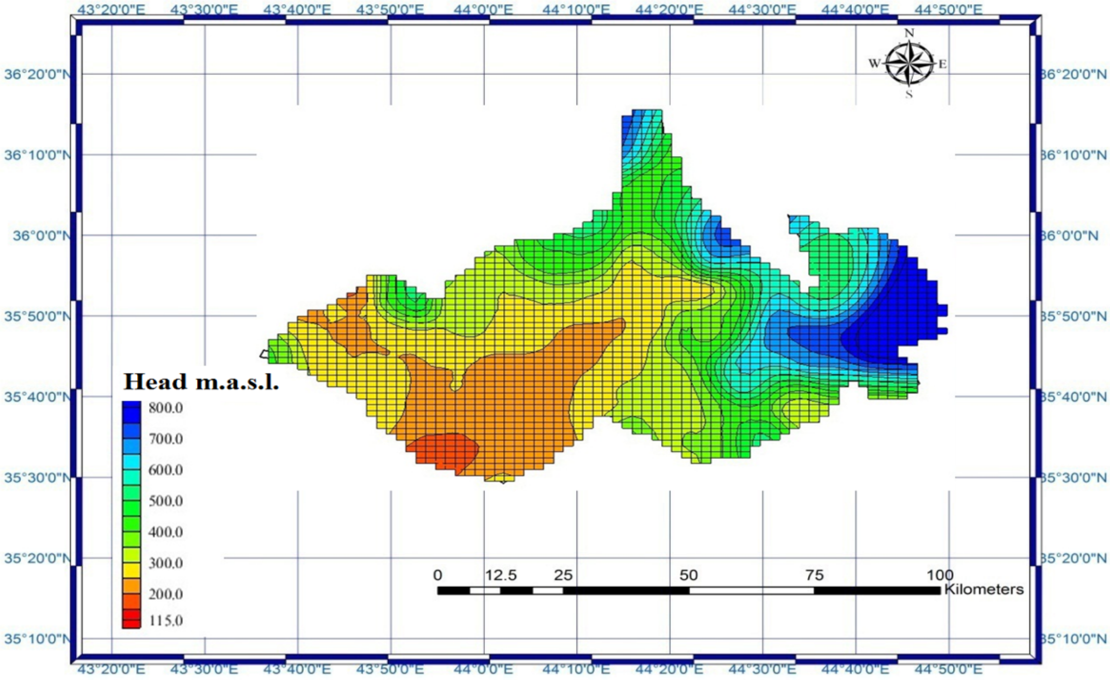


Fig. 9. Hydraulic heads after steady-state simulation

RESULTS

Model Calibration

Calibration is the process of modifying model inputs to reach the desired degree of equivalence between model simulations and the natural groundwater flow regime. It is specifically the comparison of simulations with known or measured field values (usually water table levels in unconfined aquifers). The observation coverage in GMS could be used in the calibration process when the observed values from the field would automatically be compared with the calculated values by the model. For the model of the middle section of the Lesser Zab River Basin, calibration was accomplished by sequentially modifying inputs to reach comparable head values between the selected inputs and resultant head values obtained in model simulation, compared to measured field head values (Table 2). A scatter plot of the measured against simulated water heads was used to show the calibration fit (Fig. 10). The coefficient of determination (R^2) value (often referred to as the goodness of fit) is computed. The scatter plot shows an R^2 equal to 0.99; i.e. excellent fit, (Nash-Sutcliffe efficiency coefficient of 1). For this model, the inputs of transmissivity, recharge, and boundary heads were slightly modified allowing hydraulic heads in 23 cells to more closely match observed heads with the outputs of the steady numerical model.

Table 2. The average observed water table (m.a.s.l.) during 2014 and computed values of the Bai Hassan aquifer wells (After Al-Shammari, 2015)

Well No.	Observed Value	Computed Value	Well No.	Observed value	Computed value
No.3	199	197.31	No.18	287	288.14
No.5	211	211.61	No.20	297	296.43
No.6	194	192.35	No.25	353	353.63
No.8	186	185.53	No.26	341	342.24
No.10	254	255.07	No.37	262	260.15
No.11	271	271.72	No.38	253	251.96

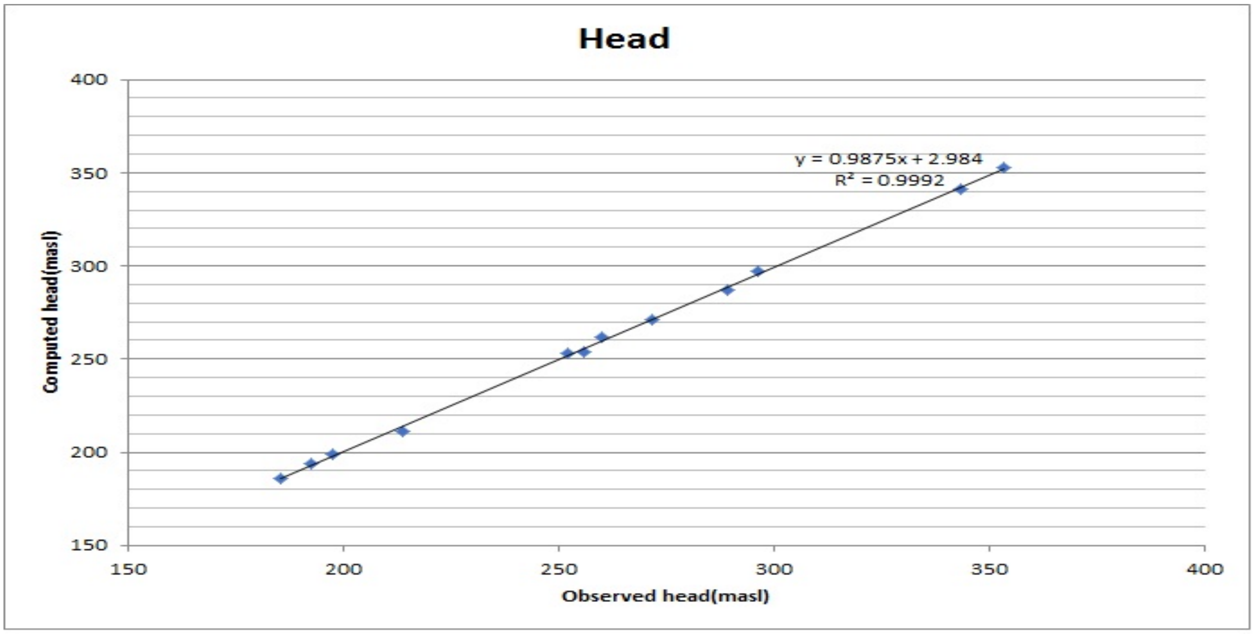


Fig. 10. Scatter plot of computed versus observed head values for steady state condition

Transient Simulation

Transient simulations involve the change in hydraulic head with time. The first attempt in transient simulation incorporates the output heads of the steady state model as inputs in the transient simulation. Transient state modeling can help reveal previous non-unique numerical steady-state solutions, and therefore help narrow the range of potential variability in model input data. Sources and sinks are added to the model to accommodate flow changes with time. Recharge was the most important source factor included in this simulation. Recharge varies due to the differences in climatologic factors associated with the topographic differences in the basin, and seasonal and yearly variation in precipitation. In particular, groundwater recharge is an influential factor during approximately 2-3 months in a year according to the calculations of water surplus during the wet winter season (Al-Shammari, 2015).

A recharge flow package (RECHARGE) was added to the MODFLOW representation of the aquifer, where recharge input is represented by positive inflow rates (volume/time or L^3/T). Recharge is added to model cells, (and therefore each cell's underlying vertical column), accounting for temporal and spatial variation. Hence, the recharge assigned to the model varied from month to month. Monthly surpluses were calculated as percentages of monthly rainfall after losses were subtracted, then converted from mm/month to m/day. Pumping wells are represented in the model as sinks, negative values, which describe point locations of discharge (L^3/T) from the aquifer. Specific yield was selected on the basis of average geological and aquifer properties and full vertical well penetration of the aquifer thickness was assumed in the MODFLOW transient state modeling (Ashri-2, 2018).

Time Stepping in Transient Simulation

One-year simulations were broken down into 12, monthly stress periods with daily time steps. These simulations included the identified sinks (wells) and recharge input into the model domain. The model output is an incremental monthly head distribution/ flow map that showed heads were decidedly dependent on the assigned boundary conditions and the distribution of groundwater recharge and sinks. The calculated head values varied slightly for each time step. The calculated hydraulic heads after 1-year pumping and recharge simulation were estimated assuming a withdrawal of groundwater of -1152 m^3 / day. The discharge of each well was estimated to be 20 l/sec with the assumed pumping duration of 16 hours/day.

This assumption was used just for the steps when there was no water surplus and a need for groundwater pumping. Effective surplus was estimated using rainfall (Fig.11) and subtracting evapotranspiration losses. One-year simulation showed very small differences in hydraulic heads, and overall little groundwater depletion over that time period. Another simulation was run with sinks for one year divided into 2 stress period (wet season and dry seasons).

The first 6-month stress period started in November through April (the wet season), while the second one started in May through October (the dry Season) (Figs. 12 and 13). In simulations of wet seasons versus dry seasons it should be noted that recharge in the basin is most prevalent during two months of the year (February and March) with the resulting surplus being uploaded to the model as an average 18 % of the total monthly rainfall. Another analysis was run for just these surplus months. For the surplus month analysis, the February recharge was calculated as 35.54 mm/month (0.00126 m/day), while in March the surplus was 19.41 mm (0.00062 m/day). These comparisons of dry and wet seasons clearly identify groundwater recharge as a strongly influencing factor in the vulnerability of local inhabitants to potential groundwater scarcity.

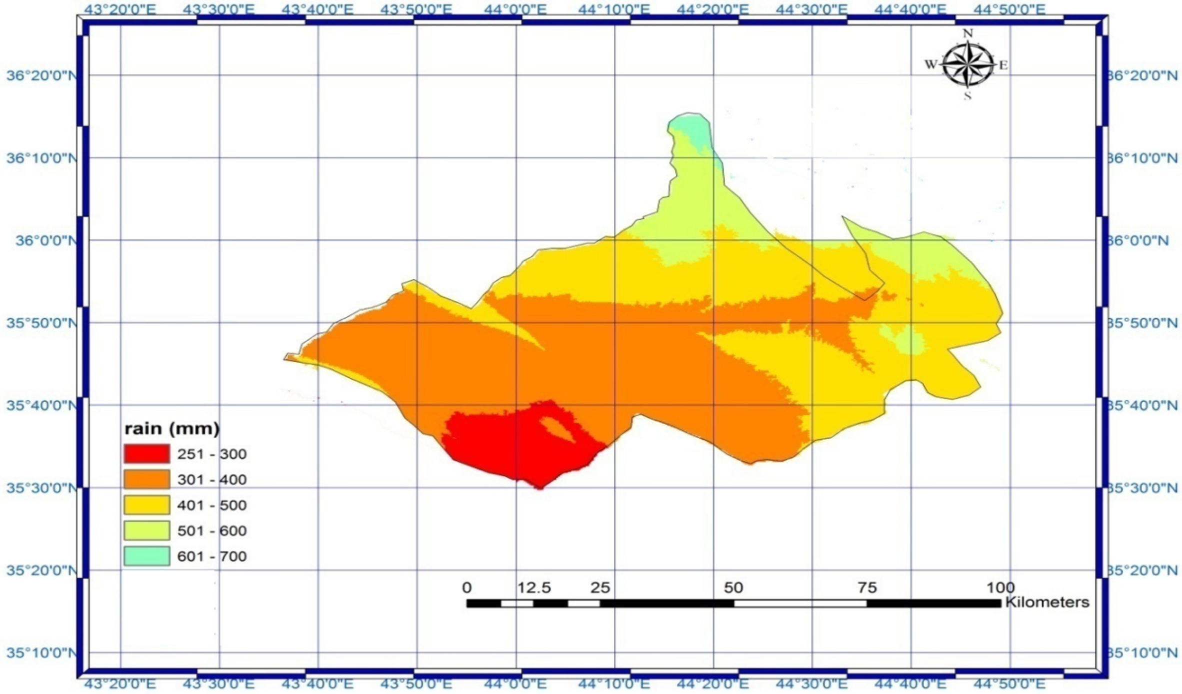


Fig. 11. Rainfall distribution in the modeled area

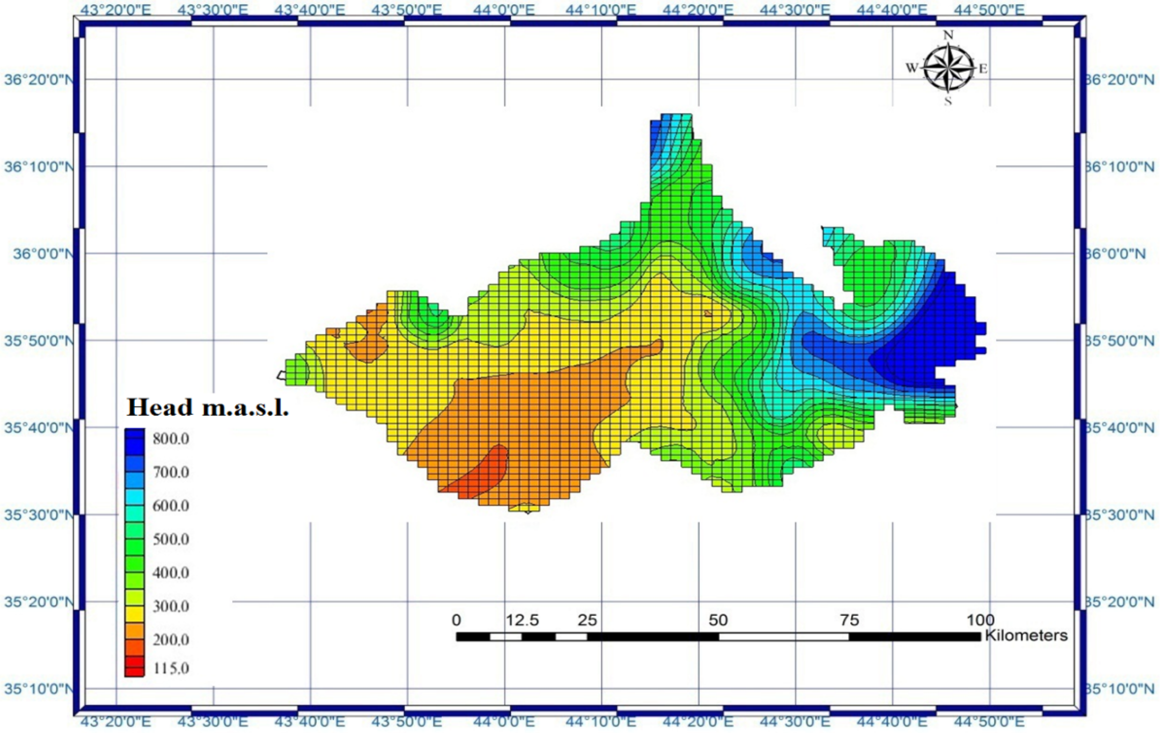


Fig. 12. Transient simulation for the wet season

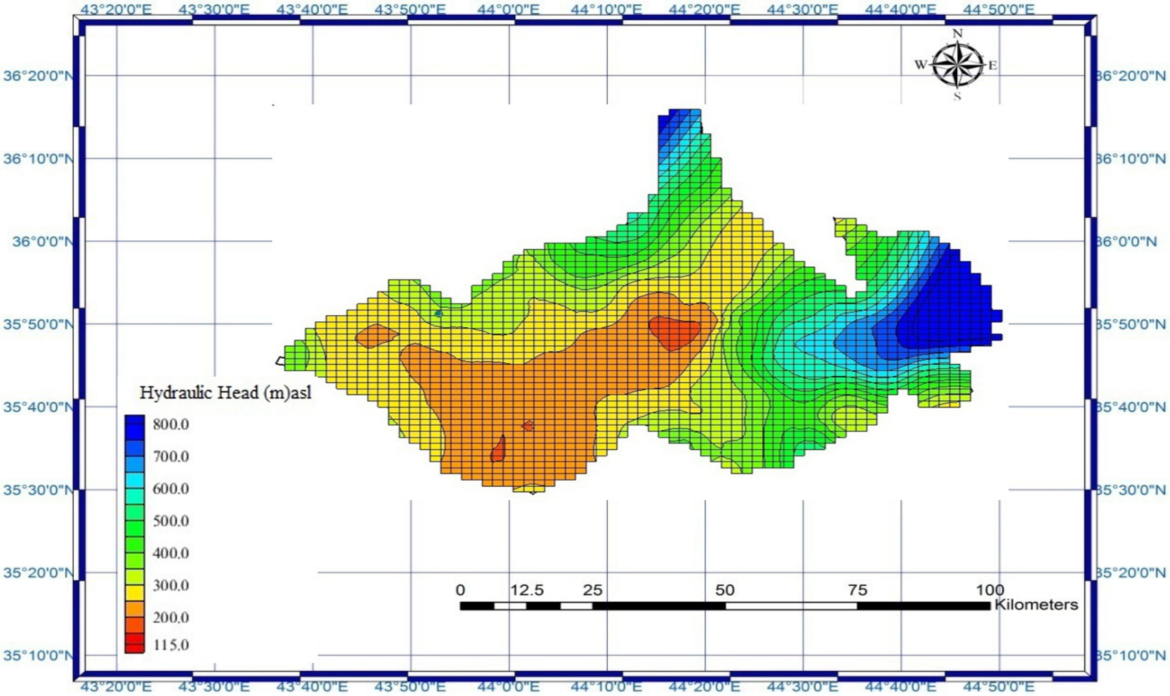


Fig. 13. Transient simulation for the dry season

Predictive Simulation

The model for the middle section of the Lesser Zab Basin may be used to predict future groundwater flow conditions, such as simulated estimates of the unconfined aquifer's water table levels response to different pumping scenarios for future production well fields. It can also predict the pumping rates that would cause serious decline in the water table. Predictive modeling was run for five and ten years from the present. This study assumed pumping from 500 new wells over the next 10 years (50 new wells drilled each year over that time period) with each well with discharging 20 l/sec for a duration of 8 hours daily. After running two simulations for every five years, the results show an appreciable drawdown in some areas (Figs. 14 and 15).

The main reason for this high drawdown within the middle parts of the basin is the urbanization and consequently increases the population while in the other parts of the basin there was governmental buildings and large restricted areas and it is not allowed to drill groundwater wells there.

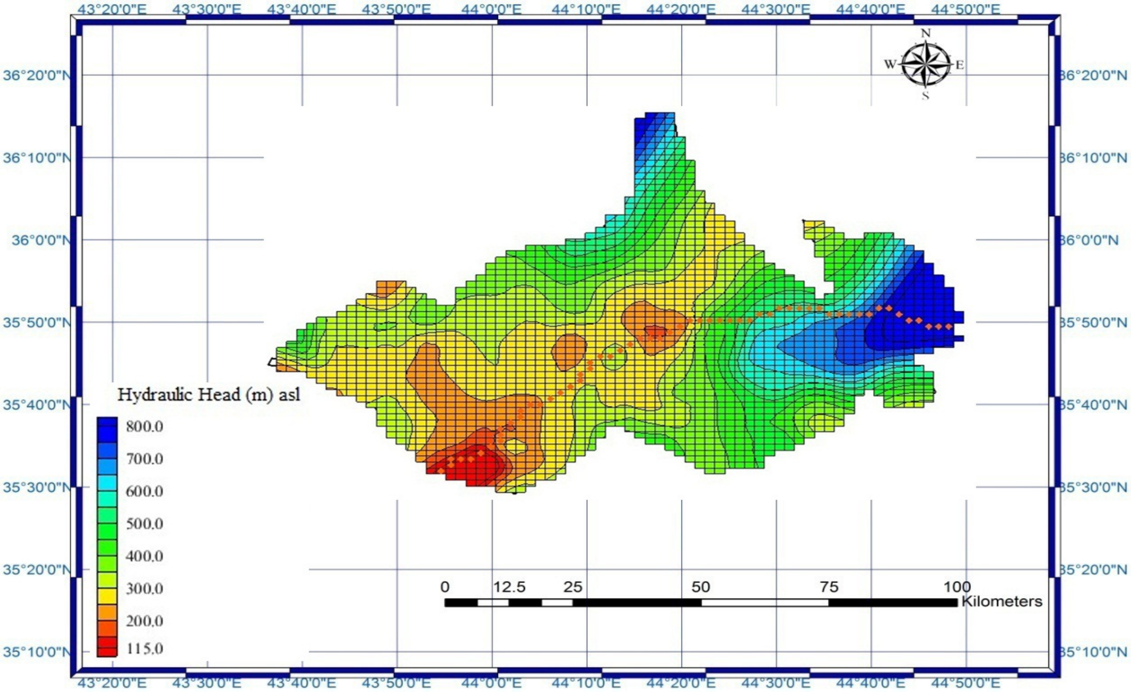


Fig. 14. Predictive simulation after 5years

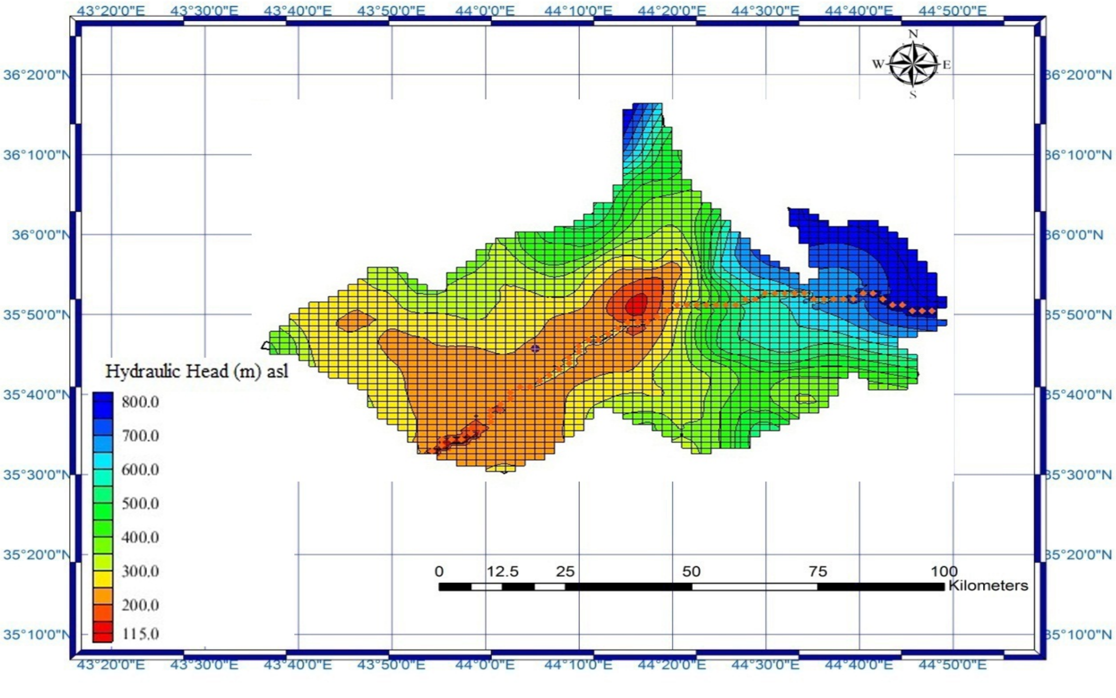


Fig. 15. Predictive simulation after 10 years

DISCUSSION

In this middle reach of the Lesser Zab River Basin, groundwater flow is generally from the upper areas of the low folded zone toward discharge areas near the river. In southerly parts of the basin's middle reach, groundwater flow patterns are more parallel to the river flow. Numerical modeling of the groundwater movement under transient conditions reveals that, under many pumping scenarios, there will be a decrease in hydraulic head of the unconfined aquifer in the modeled area on both sides of the Lesser Zab River. Reductions in hydraulic head and water table elevations are projected to increase with time. Groundwater gradients towards some sections of the river would be expected to decrease and even reverse in the middle section of the model. Eventually, sections of the river which are normally gaining reaches would be expected to transition to losing reaches, and small natural springs and marshy areas could be diminished or go dry, reducing wildlife habitat and stressing ecosystems. The numerical model used in this study was most sensitive to recharge input. The model was calibrated over a year. Modeling results indicate that drawdown effects would be expected to be most prevalent in the central basin, specifically northern Alton Copri, southern South Erbil and perhaps western Qardaso sub-basins, and to the southwest in the Daibaga and Bai Hassan sub-basins

CONCLUSIONS AND RECOMMENDATIONS

The continuous decline of hydraulic head in the middle area of the Lesser Zab Basin will require new water management policies to prevent the depletion of groundwater resources, and avoid an increase in the deterioration of its quality. Considerations for sustainable water use should probably aim at maintaining or reducing per capita water consumption, and improving water conservation practices. While urbanization and growing population have encouraged the drilling of additional groundwater wells in many parts of the basin, some areas have restricted groundwater development. The resulting model predictions allow greater insight into the potential consequences of pumping the unconfined Bai Hassan aquifer and provide science-based input to resource management decisions. Some recommended measures might include:

1- Optimization of groundwater exploitation,

2- Reduce, where possible, groundwater utilization especially in the middle and south parts of the aquifer in the study area.

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