Modeling Water Supply and Demand for Effective Water Management in the Sana’a Basin in Yemen

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Abstract:

Modelling system is the core for the evaluation of water related sectors in the Sana'a Basin. The numerical modelling (MODFLOW) has emerged as an effective tool for managing groundwater resources and predicting future responses, especially when dealing with complex aquifers systems and heterogeneous formations. MODFLOW model has been used herein as a management tool for the targeted sub- basins in Sana'a Basin such (Wadi Bani Hawat, Wadi Dhahr & Al-Ghayl, Wadi Hamdan & As Sabrah and Wadi Ghayman); the most important groundwater resources for domestic and agricultural sectors in Sana'a basin. A conceptual model was designed according to the actual groundwater dynamic flow system in the 2010 Hydrosult Sana'a Basin Model. Also, the governing partial parabolic differential equation was defined, including the vertical conductivity flow between the aquifers. Total groundwater abstraction values from previous studies were compiled, including the 2015 well inventory data of National Water Resources Authority –Sana'a Basin.In this study, three simulations of groundwater development scenarios were distinguished. The first scenario is applied for evaluation of the present status and till 2025. The second and the third scenarios are focused on the effect of water augmentation i.e. decrease the present rate of groundwater abstraction to 30% and 50% respectively, with considering the highly intervention of IWRM structure of Sana'a basin on the on-going activities related to change land use, change crop pattern, value chain, marketing, modern irrigation techniques, water harvesting techniques, treated waste reuse etc.… Also other Modules were used in calculating the groundwater demand, deficit and unemployment in agricultural sector in Sana'a Basin. Scenario 3 gives a remarkable improvement of the water resources system in the four sub-basins within a reasonable period (in the year 2025), thus, it will keep the water resources sustainability; but the unemployment in agricultural sector in Sana'a Basin in scenario 3 will be is the highest value if comparing with the other two scenarios. It will reach in 2025 under scenario 2 and scenario 3 to 10432 and 14762 respectively while in scenario 1 the unemployment will disappeared in 2025. This study is recommended that irrigation systems should be improved, usage of harvesting water methods and treated waste water reuse for agriculture to avoid the depletion of Sana' Basin aquifer and to reduce unemployment in agricultural sector in Sana'a Basin.

Keywords: Groundwater Flow Model, MODFLOW, Management Scenarios, Sana'a Basin, Targeted Sub-Basins.

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نمذجة العرض والطلب للإدارة الفعالة للمياه في حوض صنعاء في اليمن

الملخص:

نظام النمذجة هو الأساس لتقييم القطاعات ذات الصلة بالمياه في حوض صنعاء. قد برزت النمذجة العددية (مودفلو MODFLOW) كأداة فعالة لإدارة موارد المياه الجوفية والتنبؤ بالاستجابات في المستقبل، وخاصة عند التعامل مع أنظمة طبقات المياه الجوفية المعقدة والتكوينات الغيرمتجانسة. تم استخدام نموذج مودفلو هنا كأداة إدارية للأحواض الفرعية المستهدفة في حوض صنعاء مثل(وادي بني حوات، وادي ظهر والغيل الفرعي، وادي حمدان والصبرة الفرعي) والتي تعتبرأهم مصادر المياه الجوفية للقطاعات المحلية والزراعية في حوض صنعاء. تم تصميم النموذج المفهومي وفقا لنظام التدفق الديناميكي للمياه الجوفية في نموذج هيدروسولت Hydrosult لحوض صنعاء لعام 2010. كما تم تحديد المعادلة التفاضلية المكافئية الجزئية والنفاذية الرأسية للتدفق بين طبقات المياه الجوفية. تم تجميع القيم الإجمالية للسحب من المياه الجوفية من الدراسات السابقة، بما في ذلك بيانات الابارعن الهيئة العامة للموارد المائية- حوض صنعاء لعام 2015. في هذه الدراسة، تم المحاكاة لثلاثة سيناريوهات مختلفة في تنمية المياه الجوفية. السيناريو الأول لتقييم الوضع الحالي حتى عام 2025. تركز السيناريو الثاني والسيناريو الثالث على تأثير زيادة المياه أي تقليل المعدل الحالي لاستخراج المياه الجوفية إلى 30% و50% على التوالي، مع الأخذ بعين الاعتبار التدخل العالي لإدارة متكاملة للموارد المائية في حوض صنعاء المتعلقة بتغييراستخدام الأراضي، تغييرنمط المحاصيل، التسويق، تقنيات الري الحديثة، تقنيات حصاد المياه، إعادة استخدام المياه العادمة المعالجة للزراعة الخ... كما تم استخدام نماذج أخرى في حساب الطلب على المياه الجوفية والعجز والبطالة في القطاع الزراعي في حوض صنعاء. يعطي السيناريو الثالث تحسنا ملحوظا في نظام الموارد المائية في الأحواض الفرعية الأربعة خلال فترة معقولة في عام 2025، وبالتالي سيحافظ على استدامة موارد المياه، لكن البطالة في القطاع الزراعي في حوض صنعاء في السيناريو الثالث ستكون هي الأعلى قيمة إذا ما قورنت مع السيناريوهين الآخرين؛ ستصل في عام 2025 في ظل السيناريو 2 والسيناريو 3 إلى 10432 و14762 على التوالي، بينما في سيناريو 1 ستختفي البطالة في القطاع الزراعي في عام 2025. الدراسة توصي بضرورة تحسين أنظمة الري واستخدام طرق حصاد المياه وإعادة استخدام المياه العادمة المعالجة للزراعة لتجنب استنزاف طبقات المياه الجوفية لحوض صنعاء وكذا تقليل البطالة في القطاع الزراعي في حوض صنعاء.

الكلمات المفتاحية : نموذج تدفق المياه الجوفية، مودفلو، سيناريوهات للإدارة، حوض صنعاء، الأحواض الفرعية.

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1. INTRODUCTION

The Sana'a Basin relies to a large extent on groundwater for both irrigation and urban water supply. Historically, water supplies were obtained from dug wells and ghayls, tapping the unconsolidated Quaternary deposits in the plain. Borehole construction and the introduction of pumps began in the 1960s and increased rapidly from the mid-1970s onwards. This enabled deeper aquifers to be exploited for irrigation and municipal supplies. Groundwater development has been largely uncontrolled. With groundwater levels' lowering often more than five meters a year, the risk of complete depletion of groundwater resources is eminent in many locations. For that reason government decided that it should become the manager of the ground water resources as to ensure that at least sufficient water will be available for drinking water in the foreseeable future. The National Water Resources Authority (NWRA) was created to fulfill the role of water manager and seven branches have been established including one for the SB. The local communities have to play an important role as local partner of the NWRA to achieve sustainable use of the water resources.

The water resources situation in the Sana'a Basin is critical in the sense that the annual abstraction estimated as 320 Mm^3 in 2015[6] and the recharge 100 Mm^3 only [7][2][1]. The domestic water use is estimated as 70 Mm^3 for 2015[6] consequently the ground water resources is depleted at an annual rate of 290 Mm^3 in 2015; so at this rate the main aquifer presently used is depleted at alarming rate. Since 1972, many studies have been carried out by different organizations and institutions, covering geological, hydrological, and hydrogeological investigations. Sources of data and information were compiled mainly from the output of these surveys[8][10][14][3]. In addition, a groundwater MODFLOW model of the SB was initially prepared by SAWAS, the Netherlands institute for Applied Geosciences in 1996[13], and then, by Hydrosult in 2010 [4].

2. MATERIALS AND METHODS

2.1Geographical Localization and Water Resources

The Sana'a Basin is located in the western highlands of Yemen opposite the Red Sea and the Gulf of Aden. There are four major physiographic units in the basin: (i) Plateau, (ii) Terraced slopes, (iii) Wadi bottom, and (iv) Highland plain. The basin has an area of some 3,200 km^2 and forms the upper part of the catchment of Wadi al Kharid, a sub-catchment of the Wadi al Jawf. The climate is semi-arid, with an average annual rainfall of 235 mm at Sana'a. In 1995, the population of the city was estimated to be about one million and reached to 2.08 million in 2004[2]. Groundwater is abstracted from four main aquifers across the basin: alluvium (mostly in the Central zone), volcanics (most dominant in the southern and south western zones, sandstones (currently exploited in the Bani Hushaish, Hamdan, and Nihm areas but also found throughout most of the Musayreka hydrologicl unit in significantly deeper horizons), and lime stones (in the Wadi al Kharid hydrological unit, i.e the northwestern and northeastern groundwater zones). Within each groundwater zones, there are a number of major wadi catchment zones, or sub-basins, a total of 22 sub-basins have been identified on the basis of surface water drainage systems and topography. The four sub-basins (Wadi Bani Hawat sub-basin no. 9, Wadi Dhahr & Al-Ghayl sub-basin no. 14, Wadi Hamdan & As Sabrah sub-basin no. 15, Wadi Ghayman sub-basin no. 19) are the targeted sub-basinin this study, see Figure (1).Table (1) presents relevant data 2015 for the four targeted sub-basins, it shows a deficit in water resources in the four targeted sub-basins and provide a first in the challenge of water resources management in particular for the Bani Hawat sub-basin.

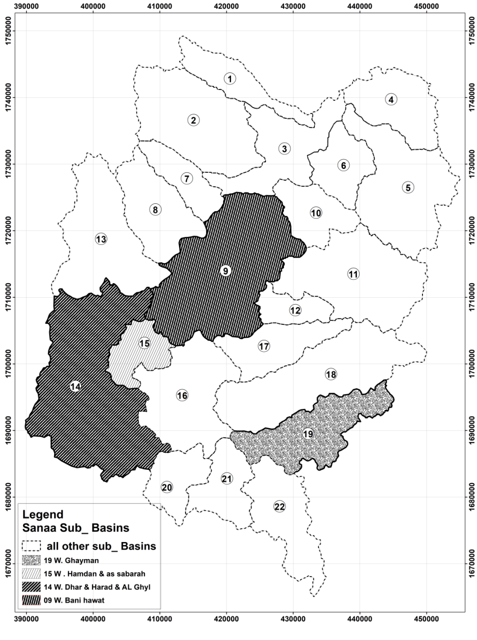

Figure (1): Location of the Four Targeted Sub-Basins

Table (1): Relevant Data for Four Targeted Sub-Basins – 2015[11]

No.	Sub-basin	Total area (^ 10^4 m2)	Irrigated area (^ 10^4 m2)	Recharge (Mm³/year)	Depletion (Mm³/year)
9	Bani Hawat	32,703	4,825	5.6	61
14	Dhahr & Al-Ghayl	36,083	1,297	7.1	16
15	Hamdan & As Sabarah	6,350	788	0.8	7
19	Ghayman	14,334	533	1.2	4
	Total area for 4 sub-basins	89,470	7,443	7,443	88

2.2 Ground Water Modeling (ModFLOW)

2.2.1 Conceptual model

Different maps and data were imported from Hydrosult Modflow that was run on 2010, the steps of running the model was established to determine the flow system and the hydraulic connection between the different aquifers in order to determine the partial differential equation governing the dynamic of groundwater flows in the four sub-basins.

2.2.2 Groundwater dynamic flow system and layered aquifer simulation

The groundwater flow systems are defined according to the conditions of the dynamic flow of each unit. The sub-basins are sub-divided into 3 layers as shown on Table (2)

2.2.3 Layered aquifer simulation

- **First simulated layer**

The Tertiary and Quaternary Volcanic Groups are bounded in the easterly and westerly directions by the Constant Head Boundary (CHB), which is located at the water divide boundary. The value of constant head is variable along the different cells, but it has a constant value for each cell for each stress period during the running of the model. These values can be adjusted during the unsteady state calibration run according to the quantity of flow to be considered for the basin to balance with the total inflow and outflow from the basin. The north direction of this layer is bounded by the GHB, representing the groundwater flow connected with the Amran Limestone formations. The flux across the boundary is calculated with a given boundary

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head value. The drain cells are assigned at the first layer, where the infiltration of seepage occurs from sewage water under Sana'a city. Also, the location of the fault-line directed south-north just a few kilometers west of Sana'a city is represented by a low value of conductivity in both simulated layers.

- **Second simulated layer**

The second simulated layer is bounded from all directions (north, east, and west) by GHB conditions, representing the flow into or out of a cell from an external source, or at the internal hydrogeological boundary. This boundary simulates the continuation of flow between two adjacent hydrogeological formations. For the Sana'a Basin model, this condition is applied at the nodes where there are hydraulic contacts between the different layers, either in x-direction or z-direction (considering the horizontal conductance or vertical conductance). Therefore, it is applied at the boundary of adjacent layers (Quaternary Alluvium, Tertiary and Quaternary Volcanic Group, and the underlying Cretaceous Sandstone), where there is a contact with Amran Limestone.

Table (2): Aquifer layers in the Targeted Sub-Basins[14]

No.	Sub-basin	First Layered Aquifer	Second Layered Aquifer	Third Layered Aquifer
9	W. Bani Hawat	Quaternary Alluvium	Quaternary Volcanic	Cretaceous Sandstone
14	W. Dhahr & Al-Ghayl	Tertiary Volcanic	Cretaceous Sandstone	
15	W. Hamdan & As Sabarah	Tertiary Volcanic	Cretaceous Sandstone	
19	W. Ghaymen	Tertiary Volcanic	Cretaceous Sandstone	

2.2.4 Model input

- **Boundary domain**

The model domain covers the dimensions of the selected region with defined co-ordinates:

X min = 386,500 - X max = 460,000 Y min = 1, 663,500 - Y max = 1,749,000

- **Grid network**

MODFLOW is used for defining the applied 2010 Hydrosult grid network for modeling and simulation studies. The boundary of SB and the boundary of the simulated model was imported to MODFLOW model for 4 targeted sub-basins. The area has been adjusted to cover the entire each sub-basin boundary region of approximately 895 square kilometers. The complete model area was assigned as active cells.

- **Constant head boundary conditions (CHB)**

The area included in the groundwater model is bounded by the watershed boundary of the four targeted sub basins. CHB is applied to fix the head value in a selected grid cell regardless of the flow system conditions in the surrounding grid cells. In the southern and western parts of sub basins no. 14, and in the eastern and southern parts of sub basin no. 19, the Volcanic Group is characterized by a water-divide hydraulic effect. The constant head value is variable along the different cells for first layer, but it has a constant value for each cell at each time period.

- **General head boundary conditions (GHB)**

In the case of the four sub-basins model, GHB is applied at the nodes where there are hydraulic contacts between the different layers. It is applied at the adjacent second layers (Cretaceous Sandstone formations for 4 targeted sub-basins with Tertiary Volcanic Group on the some places of western boundary of sub-basin no. 9).

- **Closed boundary condition (no-flow boundary)**

This boundary has been simulated in this model by inactive cells; the outside the model domain. Also, in the first and second layers, the internal boundaries with other sub-basins for the four targeted sub-basins model is considered a no-flow boundary except the southern boundary in the sub-basin no. 9, the eastern boundary in the sub-basin no. 15, and the western boundary in the sub-basin no. 19 where the urbanization areas are considered in-flow or out-flow. The hydraulic parameters of the Amran Limestone (kx, ky, and kz) are assigned a very low value. Thus, the complex of the different formations lies over an almost impervious bed of Amran limestone formations.

•Recharge boundary conditions (RCH)

Average groundwater recharge of the targeted four sub-basins were determined based on 2010 Hydrosult ModFlow, that value for each sub-basin was estimated from reservoir, catchment runoff and direct rainfall, and return flow from demand sites. The value of recharge depends on many factors, including surface topography, soil cover material, and predominant land use and vegetation type. It applied to the uppermost active wet layer of the model for each vertical column of grid cell with constant value with respect to the time factor. The model can simulate variable values of recharge rate considering the effect of aridity and climate change.

•Wells

By reviewing the different studies, the values of total yearly pumping were adjusted to conform to the projected water balance for the targeted sub-basins. The transient period is considered at the end of year 2015. Excel files were developed and imported according to the MODFLOW Software forms includes: well name, X co-ordinate, Y co-ordinate, screen ID, top elevation of screen, bottom elevation of screen, screen radius, casing radius, and stop time when pumping rate is appreciable.

•Hydraulic parameters

Pumping test data were compiled from past studies carried out by NWSA and SWEP, and were evaluated and re-analyzed within Hydrosult, 2010. The conductivity parameter includes Kx, Ky &Kz (was considered to be 10% of the value of Kx). The values of the storage coefficient and specific yield are computed mainly from analyses of pumping tests plus the general values obtained from the Mubarak model (2010)[6]were introduced as initial values for unsteady state or non-equilibrium flow. The same procedure as that applied for the conductivity coefficient for the steady state calibration was applied for the transient calibration for the values of the specific yield and the storage coefficient.

•Head observation wells

The head observation well data required by MODFLOW format includes: well name, X co-ordinate, Y co-ordinate, screen I.D., screen elevation. These data were applied for the simulation in the transient calibration run.

2.2.5. Model run setting

• Time steps

The steady state run was mainly to calibrate the aquifer conductivity parameter and its variation for both the first and second simulated layers in the targeted sub-basins. In the early seventies, the basin was not affected by heavy pumping and over-exploitation. In 2002, WEC made surveys of the water resources in SB. The available data, compiled by 2010 Hydrosult MODFLOW can be considered as the basic available data for the steady state calibration. The unsteady state calibration run covered the period from 2010 to 2015 according to the 2015 wells inventory carried by NWRA-SB. Computation for the time step is considered as 365 days (one year).

• Layer type setting

The type for each of the three simulated layers has been defined as follows:

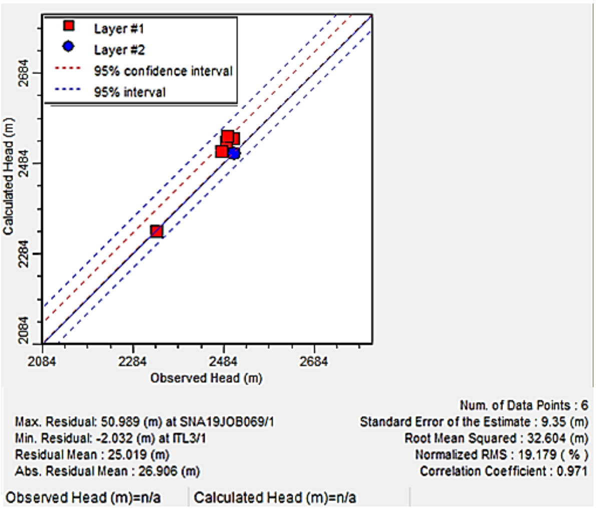
- The first simulated layer (Alluvium and Volcanic) defined as unconfined.
- The second layer, mainly Sandstone, defined as confined and unconfined.
- The method of Log-arithmetic mean inter-block transmissivity (value 20), is assigned as the numeric engine to be applied in the visual MODFLOW.
- The third layer is the limestone and defined as confined.

2.2.6. Steady state calibration runs

The steady state run was performed for year 2015, which is considered as the base year. Computation of the steady state calibration run can be summarized by the following main outputs:

- Initial head values for the transient models,
- Initial values for the invariable time hydraulic conductivity parameters (Kx, Ky, Kz),
- Water balance at the start period (2015).

Different runs (trial and error) were carried out to adjust the water budget components and to minimize the difference between computed and recorded head at the observation points. In SB, the total head difference (calculated and /measured) is about 1,000 m (from 1,800 to 2,800 masl). If a value of 5% of the ratio of error to the total head difference is acceptable, then errors up to 50 m are acceptable [9]. Therefore, the output of the calibrated steady state run can be completely accepted. In four sub-basins model, the head difference is shown on Figure (2). It shows the precision of fit of observed heads in the aquifer and the calculated heads, where most of the data points intersect the 45-degree line on the graph.



Num. of Data Points : 6
Max. Residual: 50.989 (m) at SNA19JOB069/1
Min. Residual: -2.032 (m) at ITL3/1
Residual Mean : 25.019 (m)
Abs. Residual Mean : 26.906 (m)
Standard Error of the Estimate : 9.35 (m)
Root Mean Squared : 32.604 (m)
Normalized RMS : 19.179 (%)
Correlation Coefficient : 0.971

Observed Head (m)=n/a
Calculated Head (m)=n/a

Figure (2): Scatter Graph of Calculated versus Observed Head (Steady-State Calibration Output)

•Sensitivity analysis

The sensitivity analyses were carried out by running the model with the conductivity coefficient changed by 20%. The effect on the calculated groundwater in each aquifer is recorded. It was found, from the results of the sensitivity analyses, that there are three categories of sensitivities, defined as follows:

- Low sensitivity, where the change in levels does not exceed one meter in the aquifers. This is encountered where the following wells are located: ITL9, ITL10, ITL13, and ITL14. These wells are mainly located in Quaternary Alluvium and in some parts of the Quaternary Volcanics.

- Medium sensitivity, where the change in levels ranges from one to two meters in the aquifers. There is not encountered well in this category form the targeted sub basins. If it is found well mainly located in the Tertiary Volcanics.

- Very sensitive, where the change in levels exceeds two meters. This is encountered to wells: ITL2, ITL3, and ITL5. These wells are mainly located in the Tawilah Sandstone. The same sensitivity was observed for changes of anisotropy values.

Accordingly, the calibrated values for the hydraulic parameters can be accepted and can be applied for the modeling simulation procedures.

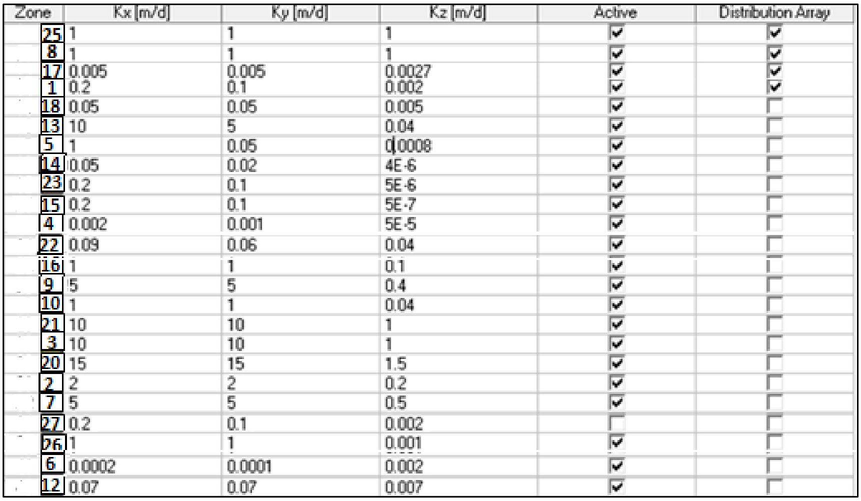
- **Calibrated flow balance graph**

The outputs of the four targeted sub-basins steady state calibrated run for each of the defined budget zones were carried out. Verification was carried out for some values; total abstraction and total recharge were confirmed with their input values and the percentage of discrepancy between the total IN and OUT for the whole targeted sub-basins do not exceed - 0.01.

- **Calibrated hydraulic conductivity**

Horizontal and vertical conductivity values were calibrated for the different water-bearing formations of the first and second simulated layers. The hydraulic parameters vary from cell to cell according to the calibrated water level in the cell with respect to the measured one. Figures (3) & (4) show the areal distribution of the horizontal hydraulic conductivity parameter in first and second Layers while the legend in Table (3).

Table (3): Calibrated Conductivity Values Legend



Zone	Kx [m/d]	Ky [m/d]	Kz [m/d]	Active	Distribution Array
25	1	1	1	☑	☑
8	1	1	1	☑	☑
17	0.005	0.005	0.0027	☑	☑
1	0.2	0.1	0.002	☑	☑
18	0.05	0.05	0.005	☑	☐
13	10	5	0.04	☑	☐
5	1	0.05	0.0008	☑	☐
14	0.05	0.02	4E-6	☑	☐
23	0.2	0.1	5E-6	☑	☐
15	0.2	0.1	5E-7	☑	☐
4	0.002	0.001	5E-5	☑	☐
22	0.09	0.06	0.04	☑	☐
16	1	1	0.1	☑	☐
9	5	5	0.4	☑	☐
10	1	1	0.04	☑	☐
21	10	10	1	☑	☐
3	10	10	1	☑	☐
20	15	15	1.5	☑	☐
2	2	2	0.2	☑	☐
7	5	5	0.5	☑	☐
27	0.2	0.1	0.002	☐	☐
26	1	1	0.001	☑	☐
6	0.0002	0.0001	0.002	☑	☐
12	0.07	0.07	0.007	☑	☐

2.2.7 Transient (un-steady state) calibration run

Information about the pumped wells was prepared in MODFLOW form. Table (4) shows the location and details of the observation wells regarding to the targeted sub-basin. With the defined parameters, automatic generation of time steps takes place and the time steps are dynamically determined during the iterations by cutting the time step size when convergence becomes difficult, and increasing it when the difficulty passes as shown on Table (5). The transient run was carried out for periods starting from the year 2015 until the year 2025. Each period covered time steps (28 or 30 or 31 upon the days of month) (as the time multiplier is taken to a value of 1.20), see Table (5). The water balance components for the budget zone outputs were selected to demonstrate the rate of variation of the hydrogeological conditions of the basin in the last 14 years. The percentage of discrepancy between the total IN and OUT in each zone budget output is in the range of (-0.04% to -0.02%).

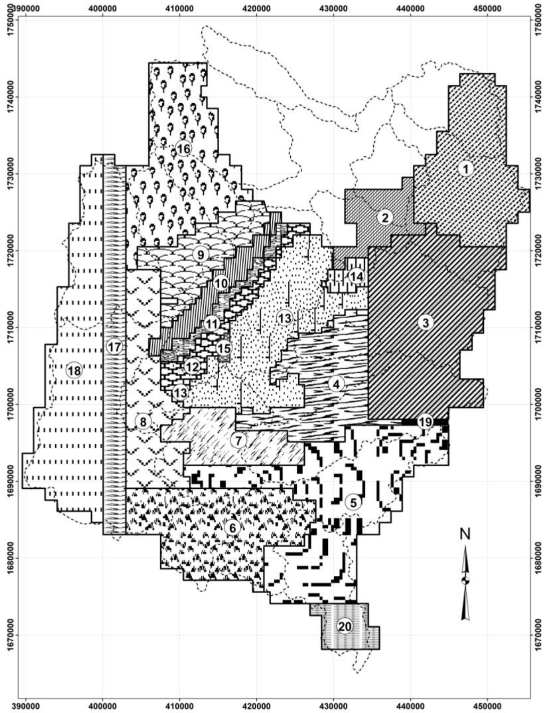


Figure (3): Steady State Calibrated Conductivity Parameters Distributions in First Layer

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Table (4): Head Observation Wells (Transient Calibration)

Sub-basin no.	Sub-basin	Well name	X_Coordinate (m)	Y_Coordinate (m)	Screen elevation (m)
9	Bani Hawat	ITL10	412700	1705300	2110
		ITL13	410620	1707625	2175
		ITL14	420860	1707950	2140
14	Dhahr & Al-Ghayl	ITL2	396709.68	1701929	2350
		ITL5	395664.52	1690954.8	2170
15	Hamdan & As Sabarah	ITL9	408600	1704000	2200
19	Ghayman	ITL3	434335	1692170	1920

Table (5): Adaptive Time-Stepping for Transient Flow

Year	Period	Start [day]	Stop [day]	Multiplier
1992	1	0	1095	1.2
1995	2	1095	2190	1.2
1998	3	2190	3285	1.2
2001	4	3285	4380	1.2
2004	5	4380	5475	1.2
2006	6	5475	6205	1.2
2010	7	6205	7665	1.2
2013	8	7665	8760	1.2
2016	9	8760	9855	1.2
2019	10	9855	10950	1.2
2022	11	10950	12045	1.2
2025	12	12045	13140	1.2

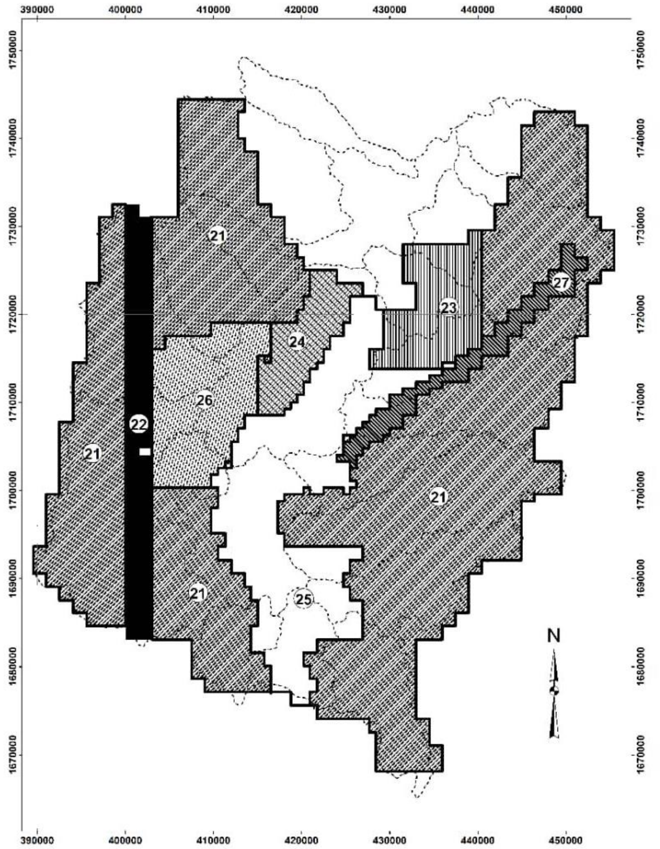

Figure (4): Steady State Calibrated Conductivity Parameters Distributions in Second Layer

2.2.8. Results and Discussion

Groundwater model (MODFLOW) was used in this study to evaluate the expected response of any development plan that could be carried out to improve the groundwater system of the Basin. The development plan can be emphasized on increasing the groundwater recharge and on decreasing and controlling the water consumptions for the different uses as follows: The first scenario is applied for evaluation of the present status. The second scenario is focused on the effect of water augmentation (decrease the present rate of groundwater abstraction to 30%) and considering the same till 2025 with the highly intervention of IWRM structure of Sana'a Basin on the on-going activities (related to change land use, change crop pattern, value chain, marketing, modern irrigation techniques, water harvesting techniques, etc…). The third scenario is focused on the effect of water augmentation i.e. decrease the present rate of groundwater abstraction to 50% considering an efficient intervention of IWRM structure and provide the necessary fund for the on-going activities. Different data of the pumped water inside the modeled area, it is of about 227.2 Mm^3/year (WEC, 2001)[14], 232.3 Mm^3/year (JICA project 2005)[5]. Also NWRA-SB wells inventory were applied for year 2015, the annual rate of pumping in the four targeted sub-basin was at a value 221.5 Mm3. So for the First scenario, the pumping water value was taken as WEC 2001 and this rate of pumping in the four sub-basins has been considered with the same pumping rate (3.5%) value until 2025. Regarding the Second and Third Scenarios, NWRA-SB wells inventory were applied for year 2015; in the Scenario2,annual rate of pumping in the four targeted sub-basin will be 155.05 Mm^3/year if rate decrease to 30% until 2020 and still the same to 2025. For Scenario3, the annual rate of pumping in the four targeted sub-basin will be 110.75 Mm3/year in 2020 if rate decrease to 50% and still the same to 2025. The model was running for the adaptive time-stepping as shown in Table (5). The Simulation results of any scenario for the year 2025 evaluate complete water balance components for each of sub-basin and water table elevation contour map was constructed.

For scenario1, water table is shown in Figure 5, and the over-exploitation areas for layer 1 and for layer 2 is shown in Figure 6 and Figure 7 respectively. The simulation results of the first scenario show that three over-exploitation areas in the first simulated layer will be developed. One area is at the sub-basin no. 09 of an area of about 160 km2, another one at the sub-basin no. 14 of about 43 km2, and the last area is at the sub-basin no. 15 of an area of about 19 km2. In addition, it is expected that two over-exploitation areas will develop in the second simulated layer.

For scenario2, water table is shown in (Figure 8), and the over-exploitation areas for layer 1 and for layer 2 is shown in (Figure 9) and (Figure 10) respectively. Comparing the over-exploitation areas with scenario1 for the two simulated layers; it demonstrates a somewhat limited improvement in the groundwater system for the Basins no. 09, 14, and 15. For the first simulated layer, the water system is improved by about 14%, and for the second layer it is improved by about 92%.See Table (6)

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For scenario3, water table is shown in (Figure 11), and the over-exploitation area for layer 1 is shown in (Figure 12). Comparing the over-exploitation areas for the first simulated layer of scenario 3 with the over-exploitation areas (Figure 6) for scenario 1; it demonstrates a somewhat limited improvement in the groundwater system for the Basins no. 09, 14, and 15. For the first simulated layer, the water system is improved by about 20%, and for the second layer it is improved by 100%. See Table (6).

Table (6) illustrates the impact of applying the various scenarios. It should be noted that most advantage is gained through applying scenarios 2 & 3.

Table (6): Evaluation of the Results of the Proposed Scenarios in the Targeted Sub-Basins

Scenarios	Predicted Over-Exploitation Areas (Km2)		Water Potentiality Improvement (%)	
	1st Simulating Layer	2nd Simulating Layer	1st Simulating Layer	2nd Simulating Layer
Scenario 1	222	13.5	---	---
Scenario 2	190	1.1	14	92
Scenario 3	178	---	20	100

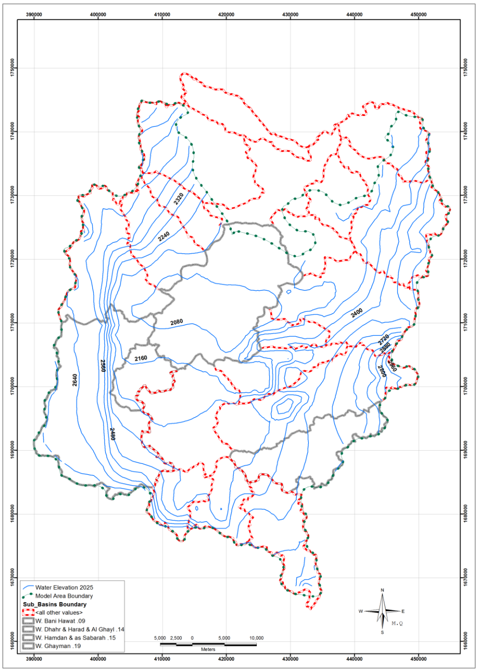

Figure (5): Water Table Elevation Contour Map for the year 2025 (Scenario 1)

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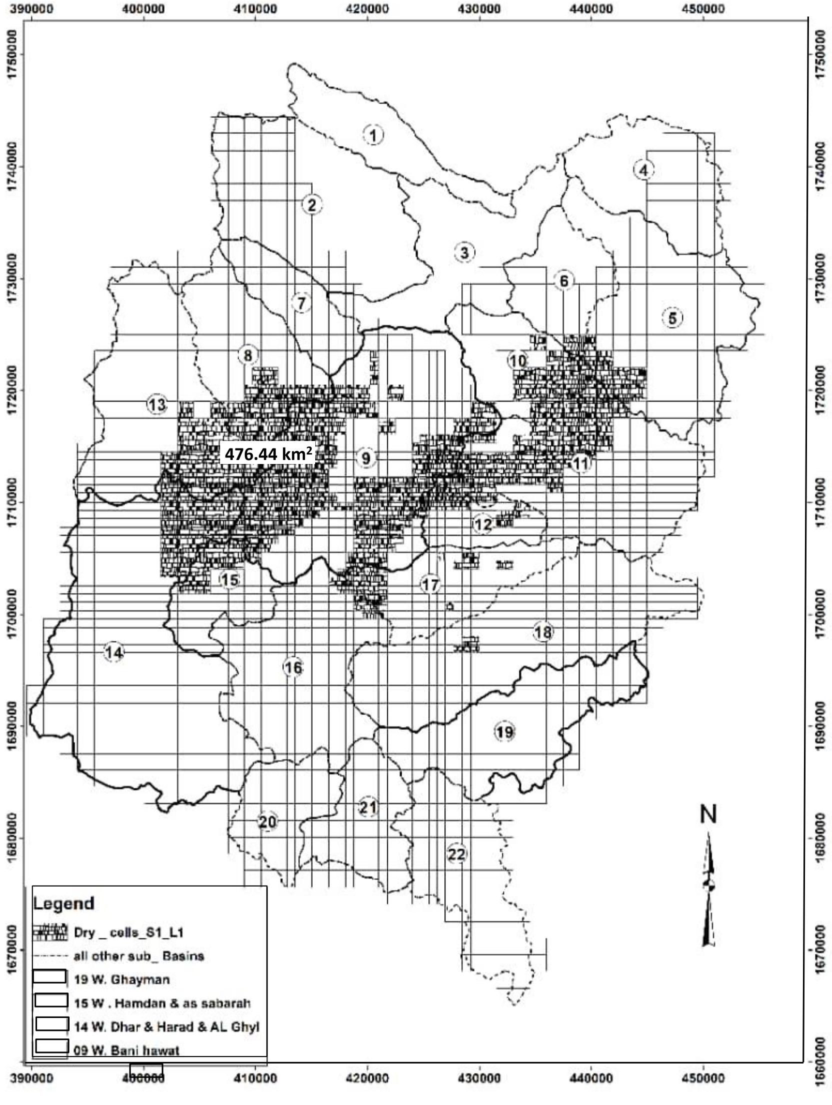

Figure (6): Expected Over-Exploitation Area in First Layer for the Year 2025 (Scenario 1)

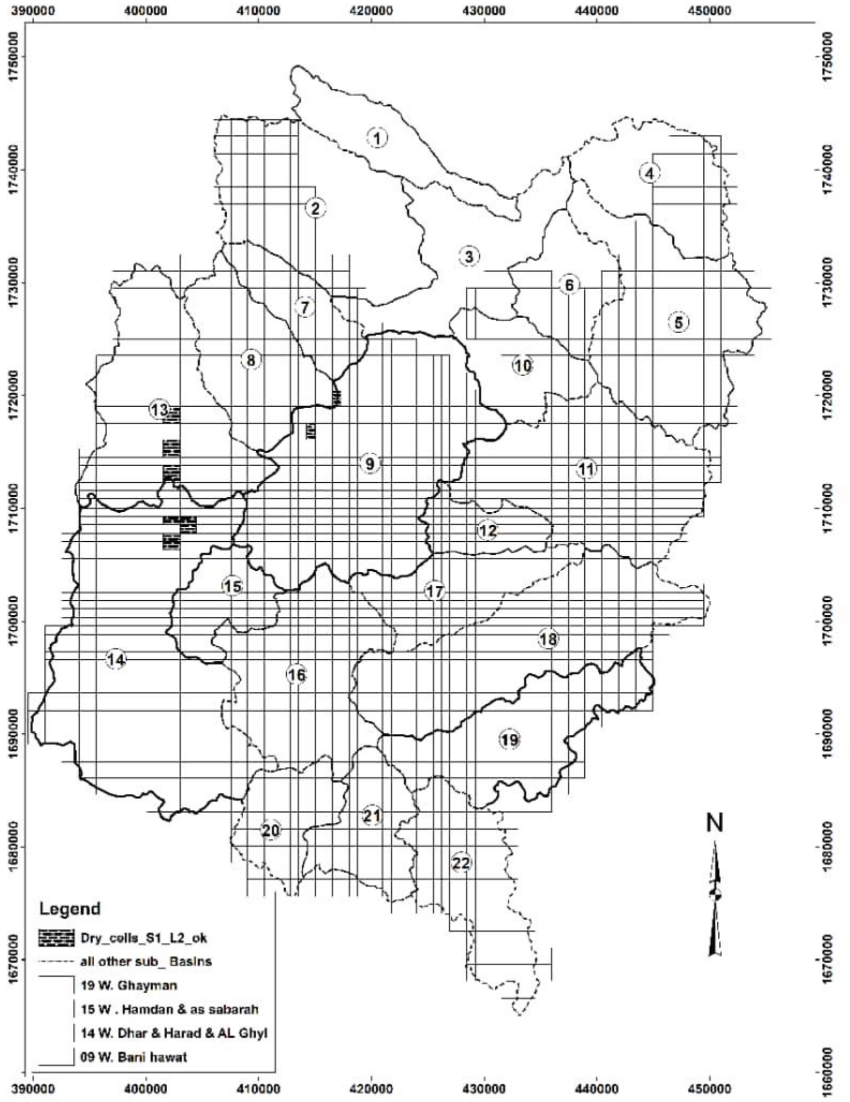

Figure (7): Expected Over-Exploitation Area in Second Layer for the Year 2025 (Scenario 1)

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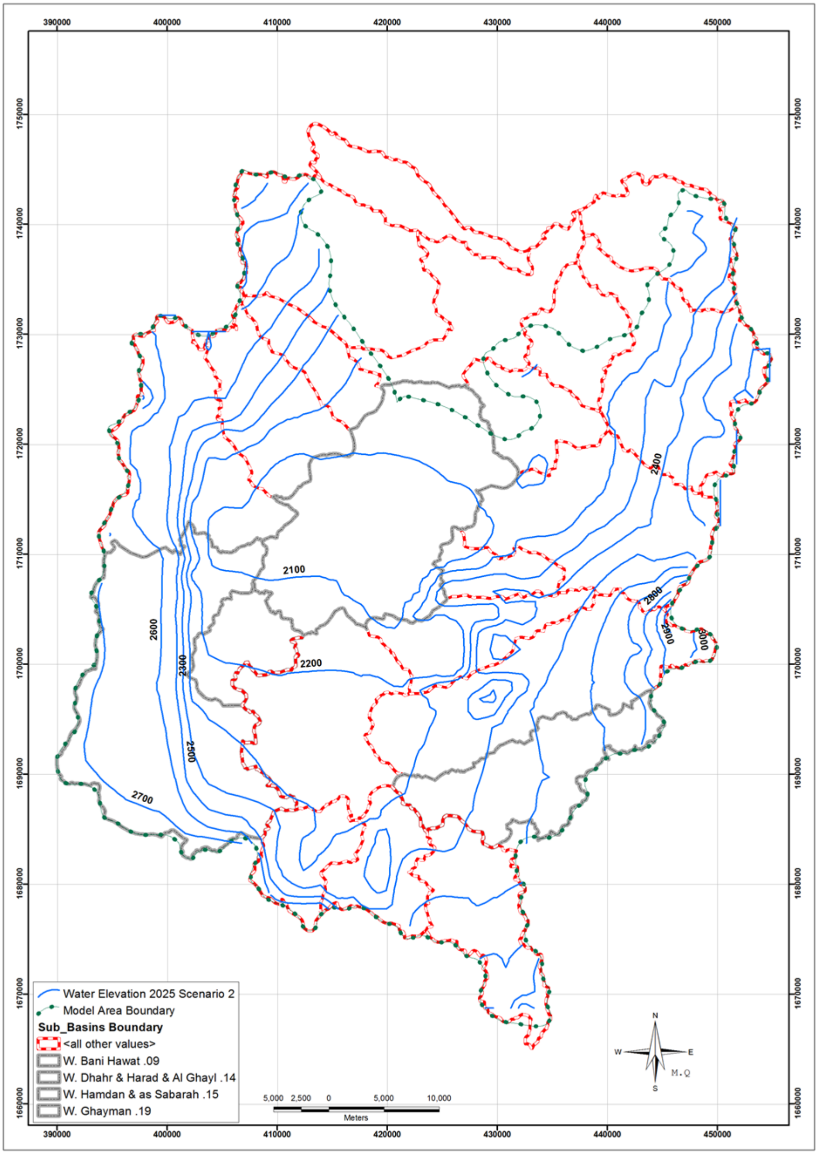

Figure (8): Water Table Elevation Contour Map for the year 2025 (Scenario 2)

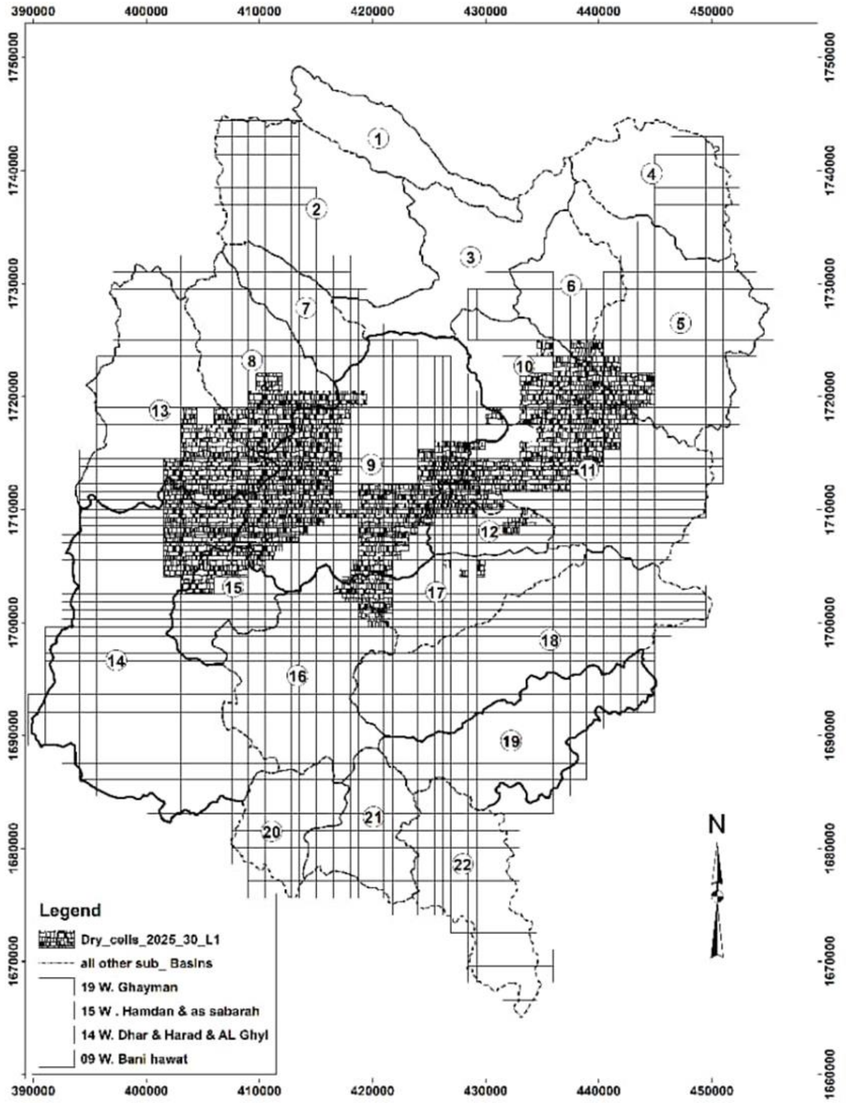

Figure (9): Expected Over-Exploitation Area in First Layer for the Year 2025 (Scenario 2)

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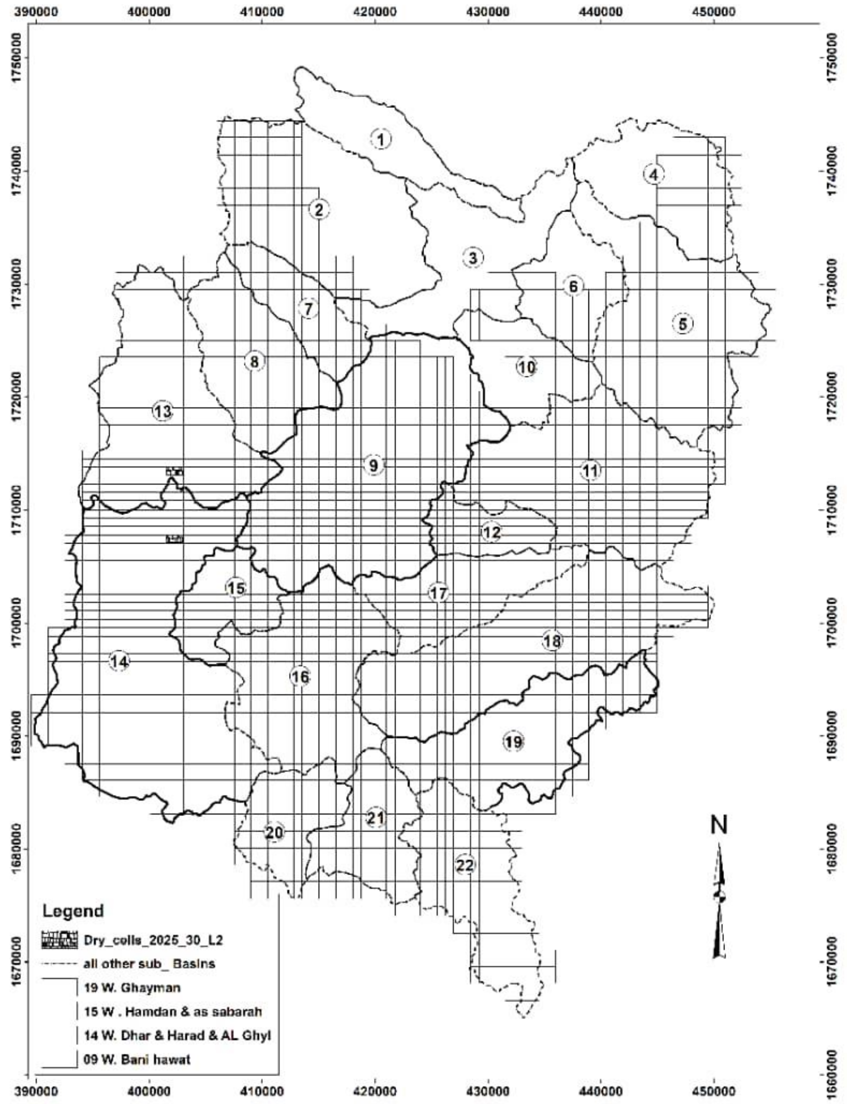

Figure (10): Expected Over- Exploitation Area in Second Layer for the Year 2025 (Scenario 2)

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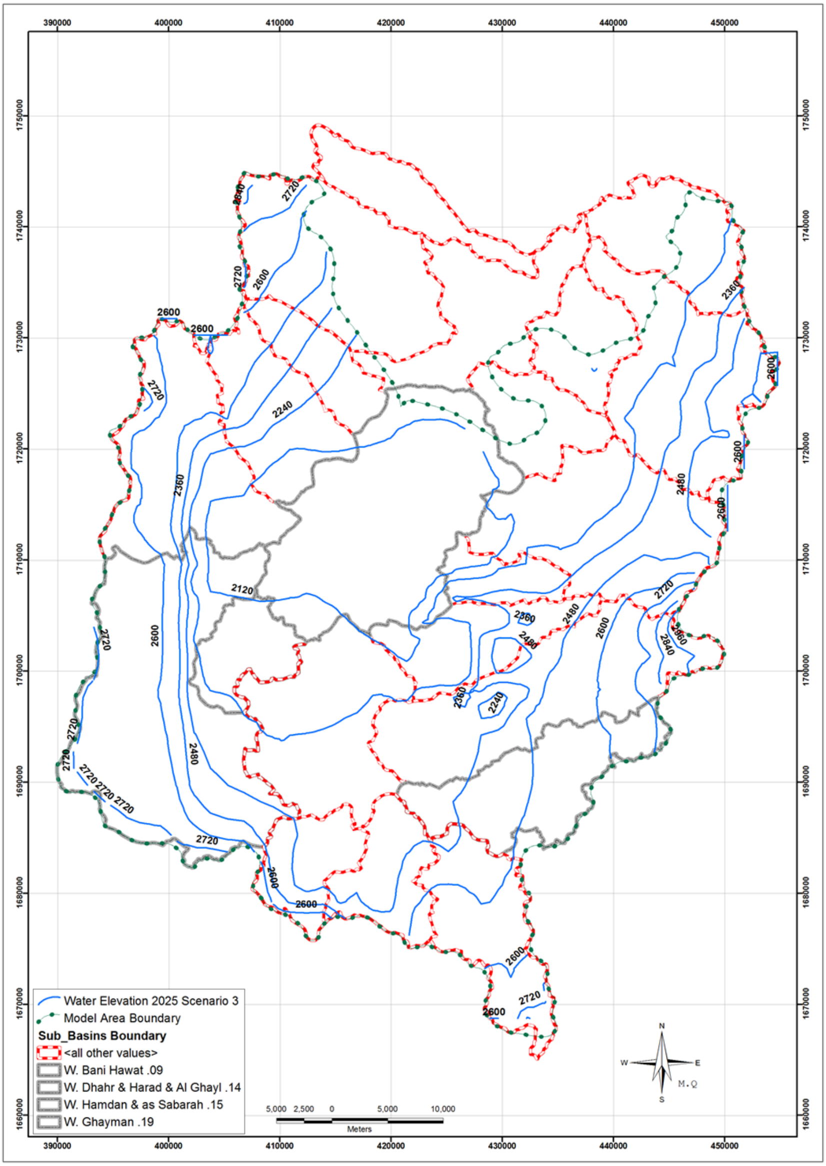

Figure (11): Water Table Elevation Contour f or the Year 2025 (Scenario 3)

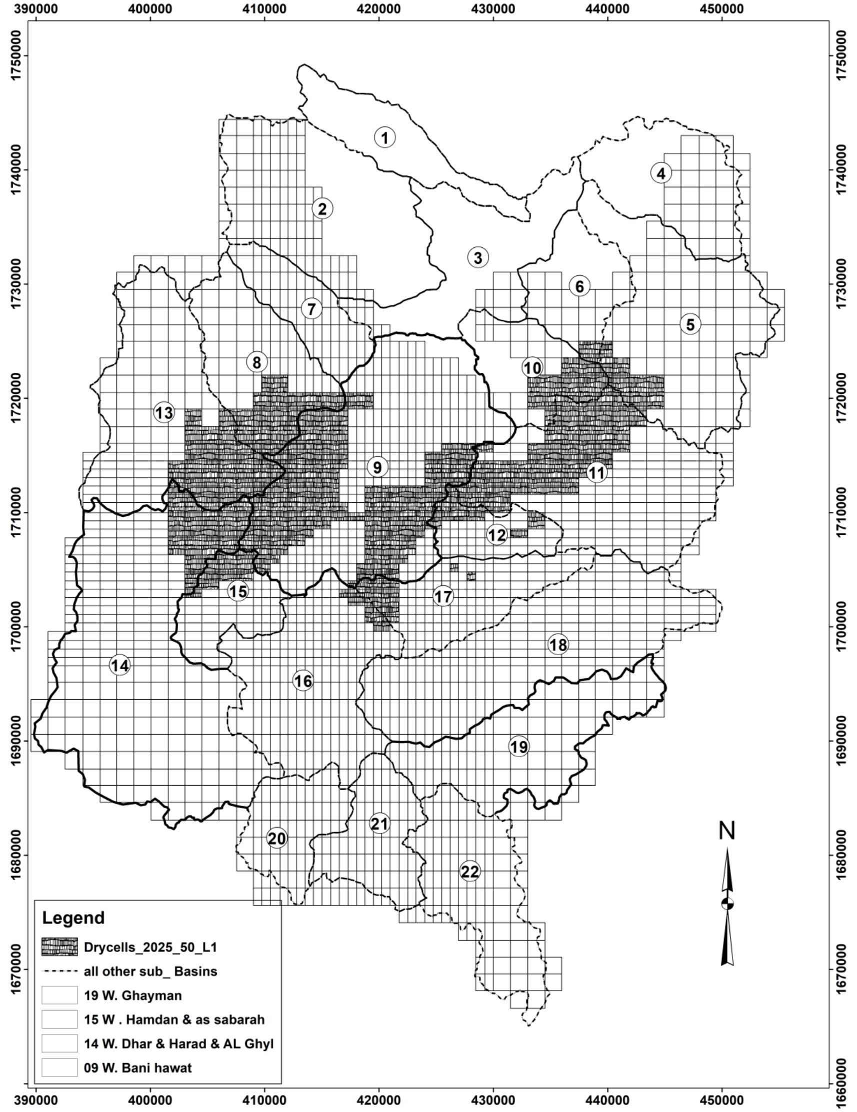

Figure (12): Expected Over-Exploitation Area Map in First Layer for the Year 2025 (Scenario 3)

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2.3 Deficit and Unemployment Modules in Agricultural Sector

The impact of ground water abstraction on the employment in agricultural sector was calculated according of water requirement for all sectors (domestic, irrigation and industrial) and supply; abstracted volume which is known from is the output of the model i.e.the water budget. Furthermore the deficit in the agricultural water demand can also be calculated after giving priority of the groundwater supply to domestic and industrial demands.

2.3.1 Domestic water demand

Assessment on groundwater use for domestic water supplies depends on the growth rates and the per capita water consumption. The population in Sana'a basin along the time horizon is extrapolated based on the population of 2.08 million in 2004 census. In this paper the population growth rate and the per capita water consumptions are taken from the values of WEC2000 [14] as 5.6% (70l/day) for Urban, 3.25% (35l/day) for urban –rural and 2% (21l/day) for rural zones. Also the per capita water consumptions are taken from the values of WEC 2001. so the calculated domestic water demand for urban, urban-rural and rural zone for 2005 was 42.6 Mm^3 (33.4, 6.6 and 2.6) respectively. With the same growth rate, it is expected that the domestic water demand will reach to 116 Mm^3 for 2025.

2.3.2 Industrial water demand

The groundwater demand for industrial activities in Sana'a Basin was founded as 3.78 Mm^3 in 2000 [14]. Due to the un cleared vision in the industrial activates in Sana'a Basin, so in this study, the industrial water demand in Sana'a Basin was calculated with 3.0% growth rate which is equal to 4.35 and 7.86 Mm^3 in 2005 and 2025 respectively.

2.3.3 Agricultural water demand

The irrigated area for 2000 was 23400 hectare (10300, 9130, 3530 and 420) for qat, mixed cereals, grapes and fruits trees respectively [14]. In this study, the total irrigated area increased by average value equal 3.5 % till 2005 (27791 ha) as previous abstraction growth rate, 1% till 2010, 0.8% till 2015 and 0.6% till 2025. The net crop water requirement was calculated using the crop water requirement programme (CROPWAT for Window). It is 5466, 5256, 6365and 8268 m3/ha/a for qat, mixed cereals, grapes and fruits trees respectively. These values are closer to the values of Ministry of

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Agriculture 2005.Hence the irrigation water requirement (IWR) for each crop with Medium Irrigation Efficiency (MIE= 65%) is 8330, 8000, 9700 and 12600 m3/ha/a for qat, mixed cereals, grapes and fruits trees respectively, and IWR for all crops in the year 2000 is 207 Mm3/a which is likely to be close to the groundwater used for irrigation during that year which was 205 Mm3.

2.3.4 Deficit in agricultural water demand

Regarding to the calculation of the total water demand in the Sana'a basin as described in the above section, the deficit in agricultural water demand can be calculated after giving priority of the groundwater supply to domestic and industrial demands as follow:

Deficit= supply – demand..(1)

Where:

Supply: is the abstraction obtained from the output of MODFLOW.

Demand: is the sum of domestic, industrial and agriculture groundwater demand.

2.3.5 Un-employment module

The collected data showed that the total number of employees in Sana'a Basin is 46385 in 2004 [12], in which 13900 whose were worked in agriculture, so about 30% of total labor force is working in agricultural sector for 2004 (approximately one person for two hectares). In this paper the total required employees in agriculture increased with the same rate of the irrigated area as described in section (2.3.3). So the required employees in agriculture will be (14400, 14882, 15462 and 16137) for 2010, 2015, 2020 and 2025 respectively. Unemployment required was calculated using the following formula:

Unemployment in Agricultural sector =

Deficit/Agricultural Water Demand × Employment for all Crops .... (2)

Table (4) shows the deficit and the unemployment in agricultural sector under the three scenarios. First it calculated under Business as Usual(Scenario 1). Second under use High Irrigation Efficiency (HIR=75%).Third under HIR with wastewater reuse (WWR) (90 % of domestic water consumption).

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Table (4): Deficit and Un-Employments in Agricultural sectors for the three scenarios in Sana'a Basin

1-Without new Intervention						
No.	**Scenario 1**		**Scenario 2**		**Scenario 3**	
	Deficit	**Unemployment**	**Deficit**	**Unemployment**	**Deficit**	**Unemployment**
2005	-88.8756	5288.76	-115.597	6878.897	-196.907	11717.44
2010	-82.1884	4866.468	-164.758	9755.53	-240.638	14248.47
2015	-76.9447	-4533.38	-214.895	12661.03	-287.608	16945.1
2020	-75.0313	-4398.98	-253.147	14841.63	-319.679	18742.35
2025	-78.2138	4563.546	-294.631	17190.84	-360.108	21011.22
2- With Improved Irrigation Efficiency (HIE 75%)						
	Scenaro1		Scenario2		Scenario3	
	Deficit	Unemployment	Deficit	Unemployment	Deficit	Unemployment
2005	-61.2194	4128.811	-87.941	5930.993	-169.251	11414.76
2010	-53.5875	3596.099	-136.158	9137.123	-212.038	14229.2
2015	-47.2239	3153.329	-185.174	12364.82	-257.887	17220.17
2020	-44.0017	2923.768	-222.117	14758.97	-288.65	18179.85
2025	-45.6714	3020.144	-262.088	16471.31	-327.565	19961.15
3- With Improved irrigation Efficiency (HIE 75%) and Wastewater Reuse						
	Scenario 1		**Scenario 2**		**Scenario 3**	
	Deficit	**Unemployment**	**Deficit**	**Unemployment**	**Deficit**	**Unemployment**
2005	-22.871	1542.488	-49.5039	3338.685	-130.879	8826.829
2010	-4.3956	294.9752	-87.0924	5844.511	-162.972	10936.59
2015	16.15252	-1078.57	-122.228	8161.688	-194.942	13017.04
2020	37.51858	-2492.99	-141.167	9380.105	-207.7	13800.99
2025	58.75332	-3885.22	-157.754	10431.92	-223.231	14761.76

3. CONCLUSIONS

With reference to the output of scenario 1, the following conclusions can be derived;

- The over-exploitation areas in the first layer have decreased by more than 20%, where these areas were in Scenario 1 of about 222 km^2, and by applying Scenario 3; these areas covered only an area of 178 km^2.
- The over-exploitation areas in the second layer were computed for Scenario 1 of about 13.5 km^2, and this area has vanished and disappeared completely.

With reference to the output of Scenario 2, the following conclusions can be derived;

- The over-exploitation areas in the first layer have decreased by more than 14%, where these areas were in Scenario 1 of about 222 km^2, and by applying scenario 2; these areas covered only an area of 190 km^2.

- The over-exploitation areas in the second layer were computed for scenario 1 of about 13.5 km^2, where in Scenario 2 the exploitation-areas have about 1.1 km^2.
- As shown above, Scenario 3 gives a remarkable improvement of the Water Resources System in the four sub-basins by a rate of more 20%, within a reasonable period (in the year 2025). Thus, it will keep the water resources sustainability.
- It is noticed that, the unemployment without any intervention is less under scenario1 if compared with scenario 2 and scenario3. Also it is noticed that as the deficit increases the unemployment also increased. The unemployment is decreased with HIE, and WWR alternatives, it will reach in 2025 under scenario1, scenario 2 and scenario3 to-3885.22, 10431.92 and 14761.76 respectively. So there is no unemployment with scenario1from 2015 to 2025 under HIE, and WWR alternatives.

4. RECOMMENDATIONS

- Measures for water resources management: In view of the current imbalance between abstraction and total inflows to the groundwater system of the studied Wadis in Sana'a, active management of the resource is required. The management recommendations described here include the measures relevant to safeguard water quantity extraction and involves aquifer protection. Measures for aquifer protection include recommendations relating to control of abstraction and augmentation. E.g. it is recommended that irrigation systems to be improved and that losses in transport and distribution of irrigation networks be reduced.
- Different methods can be applied to increase the Groundwater Recharge, whether from Reservoir, Catchment Runoff, or Return Flow from demand sites. The available potential to use water-harvesting methods in Four Sub-basins is very encouraging.
- Continuous monitoring, coupled with a computerised GIS database, is a powerful tool with which proper planning can be updated. Geographic Information Systems have to be applied extensively to enable various methods of storage, treatment and linkage of data and the projection of such in maps by international or national geographic coordinates.

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- Periodical accurate measurements of water level and pumped water quantities are required to ensure that there are no discrepancies between measured values during exploitation of groundwater and values predicted by the model. So use of the mathematical model technique is not only for planning, but also for follow-up and management processes. Thus the four sub-basins should enact water laws that regulate the utilisation of water within the available resources, protect them against deterioration, assign responsibilities and competence to the administrative bodies and regulate relations between these bodies

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