Using Groundwater Flow Model (MODFLOW) As a Management Tool for Targeted Sub-Basins in Sana'a Basin

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Abstract

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 (Wadi Bani Hawat sub-basin , Wadi Dhahr & Al-Ghayl sub-basin , Wadi Hamdan & As Sabrah sub-basin and Wadi Ghayman sub-basin); the most important groundwater resources for domestic and agricultural sectors in Sana'a basin . Groundwater extraction from this basin has already exceeded the safe yield of the aquifer, a sharp drop in the water table, and a dry out of most wells. Currently, more than 13000 wells including governmental, private and unauthorized wells are operating within the basin boundary. 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 were compiled after filtering the available data, including the 2015 NWRA-SB wells inventory data. These data were documented in a database and stored in soft copy (excel form). 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, etc….. 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. It is recommended that irrigation systems should be improved with the usage of harvesting water methods to reduce the losses and increase the groundwater recharge respectively in the targeted four sub-basins

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

Introduction:

Sana'a basin (SB) 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 SB is critical in the sense that the annual abstraction is 300 million m³ and the recharge 100 million m³ only. The requirement for drinking water equals the volume of annual recharge consequently the ground water resources is depleted at an annual rate of 200 million m³. It is estimated that at this rate the main aquifer presently used will be dried out in about 15 years.

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 (Russian 1982, SAWAS 1993, NWAS 2000, 2004, WEC 2002, NWRA 2004, 2005, 2006, GAF, 2007, and

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NWRA-SB Monitoring Network information)[1,4,6,8].
In addition, a groundwater MODFLOW model of the SB was initially prepared by SAWAS, the Netherlands institute for Applied Geosciences in 1996[6], and then, by Hydrosult in 2010. The study presented herein used MODFLOW to construct a groundwater flow model for the targeted sub-basins using 2010 Hydrosult model[2] and the NWRA-SB 2015 wells inventory data as input[7]. This model was then used as a management tool for assessing the current situation and forecasting future responses to assumed coming events of main four targeted sub-basin in Sana'a basin. Three different future pumping scenarios have been considered.

Description of the Targeted Sub-Basins:

Sana'a Basin is an inter-mountain plain located in the central Yemeni highlands. Yemen covers a total area of approximately 536,000 square kilometers, and consists of 22 governorates including the four targeted 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), see Figure (1). The plain has an elevation of about 2,200 m above sea level (as l), but is surrounded to the west, south and east by mountains rising to more than 3,000 m as l. The basin has an area of some 3,200 km² 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. 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 Wadi al Kharid hydrological unit, i.e the northwestern and northeastern groundwater zones). Table (1) presents relevant data and the expected depletion rate at the end of 2025 for the four targeted sub-basins. It shows a deficit in water resources in the four targeted sub-basins and provides a first in the challenge of water resources management in particular for the Bani Hawat sub-basin.

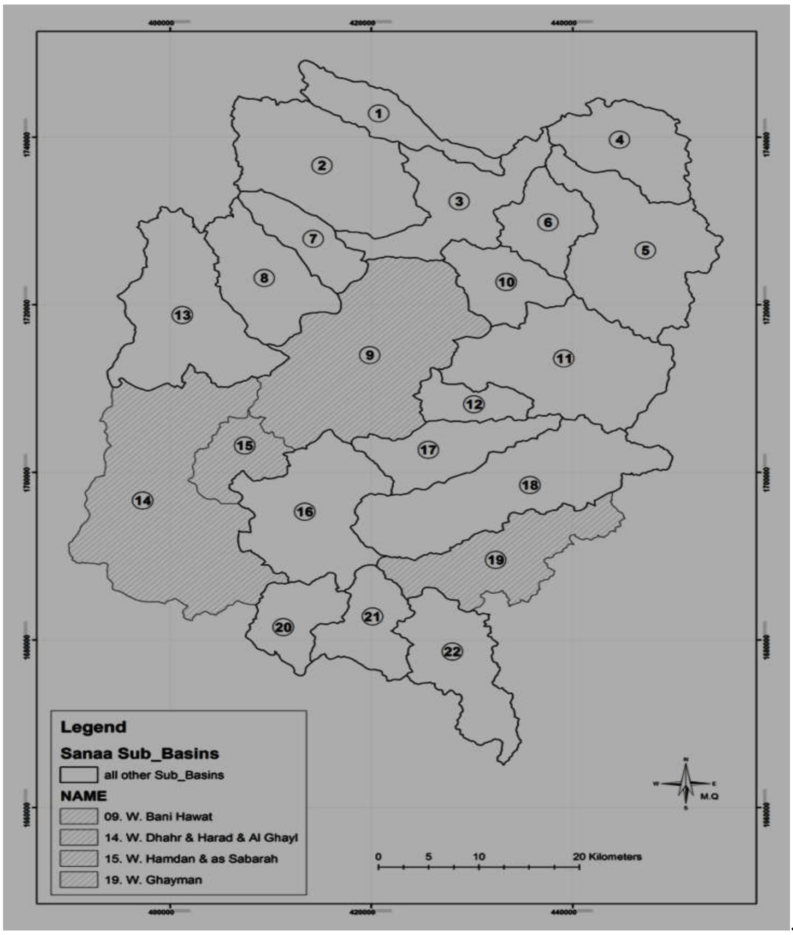

Figure (1): Location of the Four Targeted Sub-Basins

Table (1): Relevant Data for Four Targeted Sub-Basins

No.	Sub-basin	Total area (^10^4 m^2)	Irrigated area **(^10^4 m^2)**	Recharge (Mm^3/year)	Present depletion (Mm^3/year)	Depletion rate in 2025 (Mm^3/year)
9	Bani Hawat	32,703	4,825	5.6	61	40
14	Dhahr & Al-Ghayl	36,083	1,297	7.1	16	11
15	Hamdan & As Sabarah	6,350	788	0.8	7	5
19	Ghayman	14,334	533	1.2	4	2
Total area for 4 sub-basins		89,470	7,443	14.7	88	58

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.

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)

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 divided boundary. The value of the 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 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.

Table (2): Water Flow Systems

No.	Sub-basin	Water Flow Systems		
		One Layered Aquifer	Two Layered Aquifer	Three Layered Aquifer
9	W. Bani Hawat	Alluvium Sandstone	Alluvium Volcanic Alluvium Sandstone	Alluvium Volcanic Sandstone
14	W. Dhahr & Al-Ghayl	-	Volcanic Sandstone	-
15	W. Hamdan & As Sabarah	-	Volcanic Sandstone	-
19	W. Ghaymen	-	Volcanic Sandstone	-

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 the analyses of pumping tests plus the general values obtained from the Mubarak model (2010) [5] 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.

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) is defined as unconfined
- The second layer, mainly Sandstone, is 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

Steady State Calibration Run:
The steady state run was performed for year 2010, 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 (2010).

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 (Foppen 2004). Therefore, the output of the calibrated steady state run can be completely accepted. In four sub-basins model, the head difference is shown in 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 in the graph.

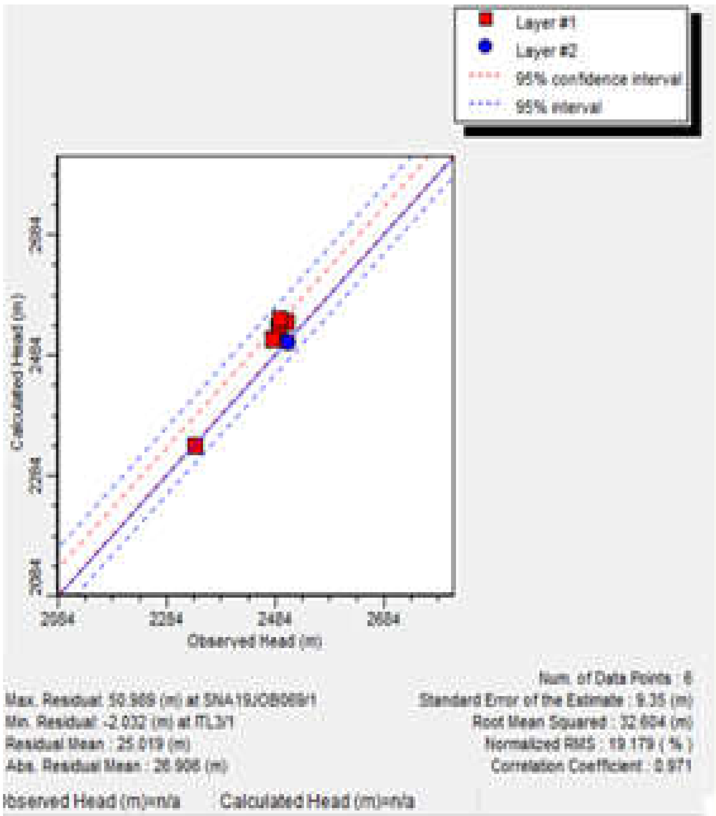

Figure (2): Scatter Graph of Calculated versus Observed Head *(*Steady-State Calibration Output*)*

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 the first and second Layers while the legend in Table (3).

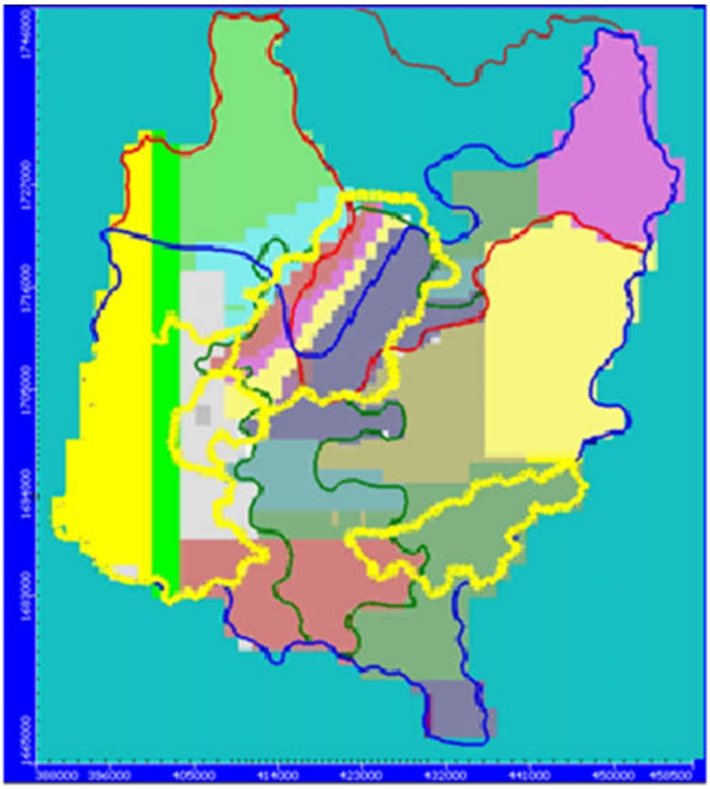

Figure (3): Steady State Calibrated Conductivity Parameters Distributions in First Layer

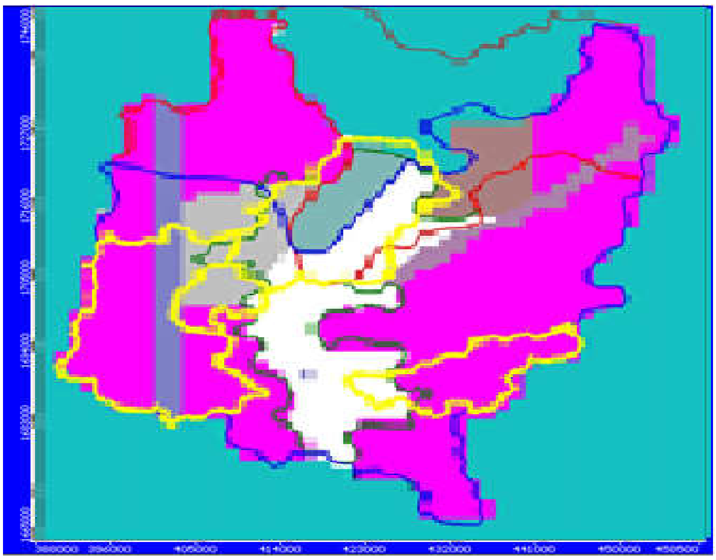

Figure (4): Steady State Calibrated Conductivity Parameters Distributions in Second Layer

Table (3) : Calibrated Conductivity Values Legend

Zone	Kx [m/d]	Ky [m/d]	Kz [m/d]	Active	Distribution Array
1	1	1	1	✓	✓
2	0.02	0.01	2E-7	✓	✓
3	0.021	0.01	2E-7	✓	✓
4	0.021	0.01	1E-7	✓	✓
5	1	1	1	✓	✓
6	1	1	1	✓	✓
7	1	1	1	✓	✓
8	1	1	1	✓	✓
9	1	1	1	✓	✓
10	1	1	1	✓	✓
11	0.005	0.005	0.0027	✓	✓
12	10	10	1		✓
13	0.02	0.01	0.002	✓	✓
14	0.2	0.1	0.002	✓	✓
15	0.05	0.05	0.005	✓	
16	10	5	0.04	✓	
17	1	0.05	0.0008	✓	
18	0.05	0.02	4E-6	✓	
19	0.2	0.1	5E-6	✓	
20	0.2	0.1	5E-7	✓	
21	0.002	0.001	5E-5	✓	
22	0.09	0.06	0.04	✓	
23	0.2	0.1	5E-5	✓	
24	0.09	0.06	0.04	✓	
25	1	1	0.1	✓	
26	5	5	0.4	✓	
27	1	1	0.04	✓	
28	10	10	1	✓	
29	10	10	1	✓	
30	15	15	1.5	✓	
31	2	2	0.2	✓	
32	5	5	0.5	✓	
33	5	5	5		
34	0.2	0.1	0.002		
35	0.0045	0.0045	2.7E-6		
36	0.02	0.01	0.0002	✓	
37	1	1	0.001	✓	
38	0.0002	0.0001	0.002	✓	
39	0.02	0.01	0.0002	✓	
40	1	1	0.001	✓	
41	0.0002	0.0001	0.002	✓	
42	0.001	0.001	0.0005	✓	
43	0.07	0.07	0.007	✓	
44	0.001	0.001	0.0001		

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 base year 2010 to the year 2015 and the output have been achieved as a result of running the model for transient state for the year 2025 for different scenarios. 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%).

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]	Time Steps	Multiplier
2002	1	0	1095	30	1.2
2006	2	1095	2555	31	1.2
2010	3	2555	4015	30	1.2
2012	4	4015	4745	31	1.2
2015	5	4745	5840	30	1.2
2019	6	5840	7300	31	1.2
2022	7	7300	8395	30	1.2
2025	8	8395	9490	31	1.2

Model Predictions:

Model predictions have been carried out to evaluate the expected response of any 155.05 Mm^3development 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 SB 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. For the evaluation of first scenario, the pumped water inside the modeled area only is of about 227.2 Mm^3/year (WEC, 2001). Estimation of the JICA project was considered for 2005[3], at a value of 232.3 Mm^3/year and considered the same value until 2015. 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 Mm^3. This rate of pumping in the four sub-basins has been considered the same value until 2025. The model was running for the adaptive time-stepping as shown in Table (5). The Simulation results for the year 2025 evaluate complete water balance components for each of sub-basin budget zones ,water table elevation contour map was constructed (see Figure 5) and the over-exploitation areas, where the groundwater level has dropped dramatically, and the water formations have dried in these locations (Figure 6) for layer 1, and (Figure 7) for layer 2. 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 km^2, another one at the sub-basin no. 14 of about 43 km^2, and the last area is at the sub-basin no. 15 of an area of about 19 km^2. In addition, it is expected that two over-exploitation areas will develop in the second simulated layer.

Simulation results of the second scenario, in which the annual rate of pumping in the four targeted sub-basin will be 155.05 Mm³/year if rate decreases to 30% and still the same to 2025 together with an efficient intervention related to (change land use, change crop pattern, value chain, marketing, modern irrigation techniques, water harvesting techniques, etc) evaluate complete water balance components for each of sub-basin budget zones ,water table elevation contour map was constructed (Figure 8) and the over-exploitation areas, where the groundwater level has dropped dramatically, and the water formations have dried in these locations (Figure 9) for layer 1, and (Figure 10) for layer 2. Comparing the over-exploitation areas for the two simulated layers, (Figure 9 and Figure 10) for Scenario2, with the over-exploitation areas (Figure 6 & Figure 7) for Scenario 1, 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%.

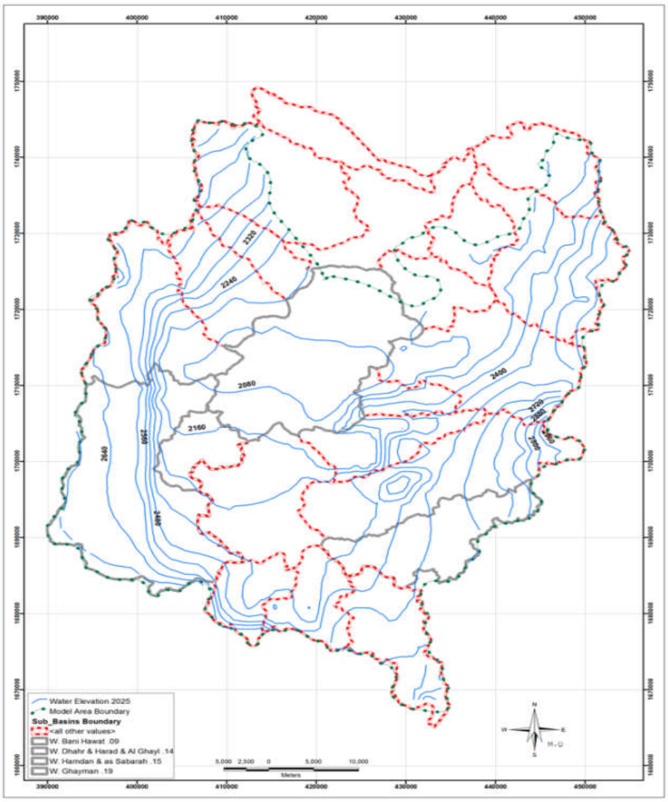

Figure (5): Water Table Elevation Contour Map for the year 2025 (Scenario 1)

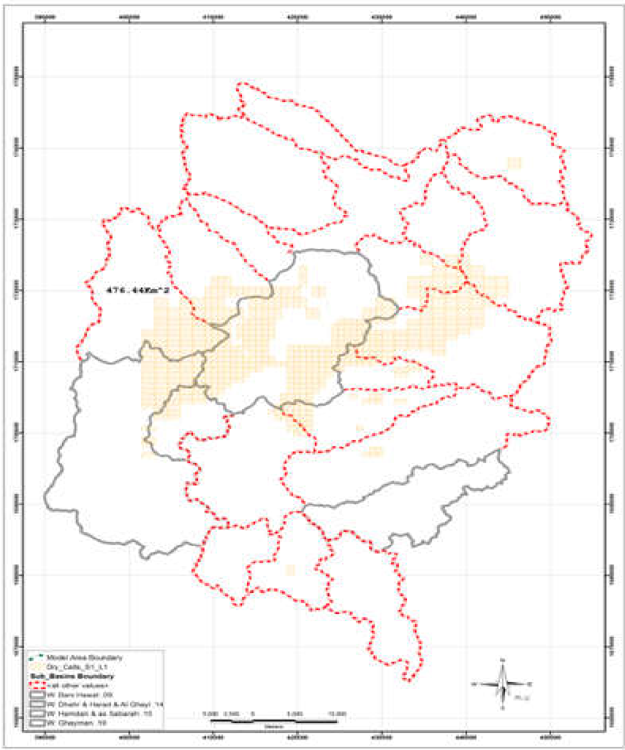

Figure (6): Expected Over-Exploitation Area in in First Layer for the Year 2025(Scenario1)

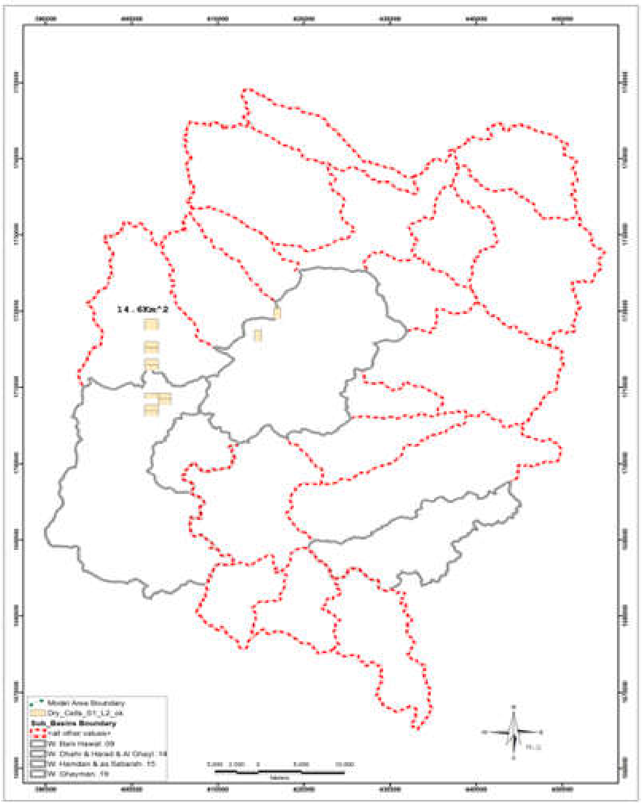

Figure (7): Expected Over-Exploitation Area in in Second Layer for the Year 2025(Scenario1)

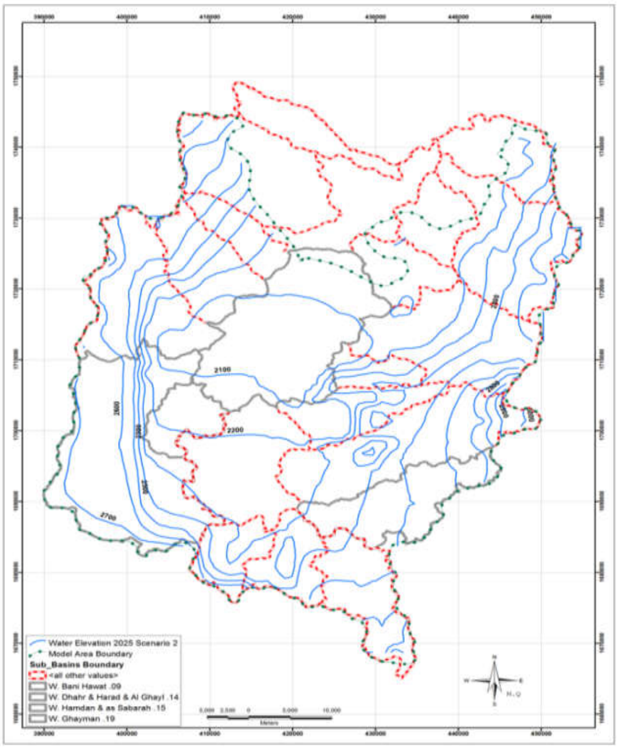

Figure (8) : Water Table Elevation Contour Map for the year 2025 (Scenario 2)

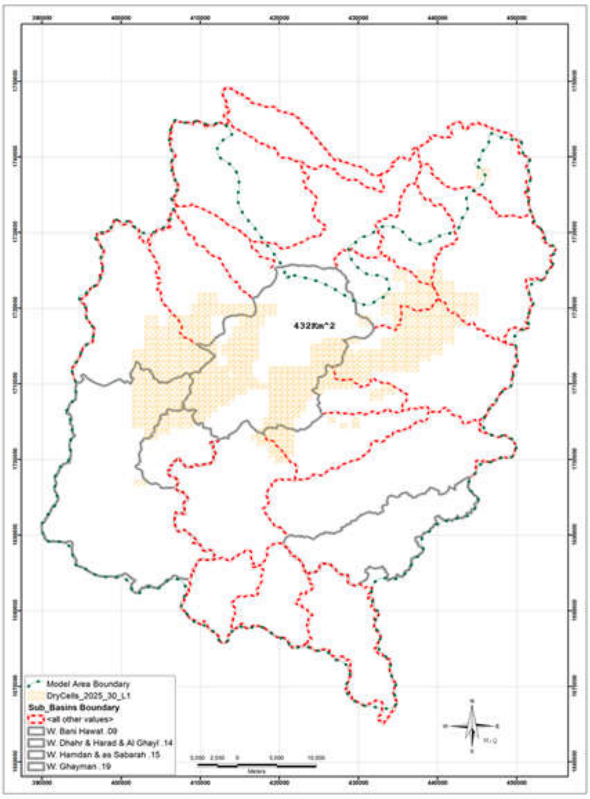

Figure (9): Expected Over-Exploitation Area in in First Layer for the Year 2025 (Scenario2)

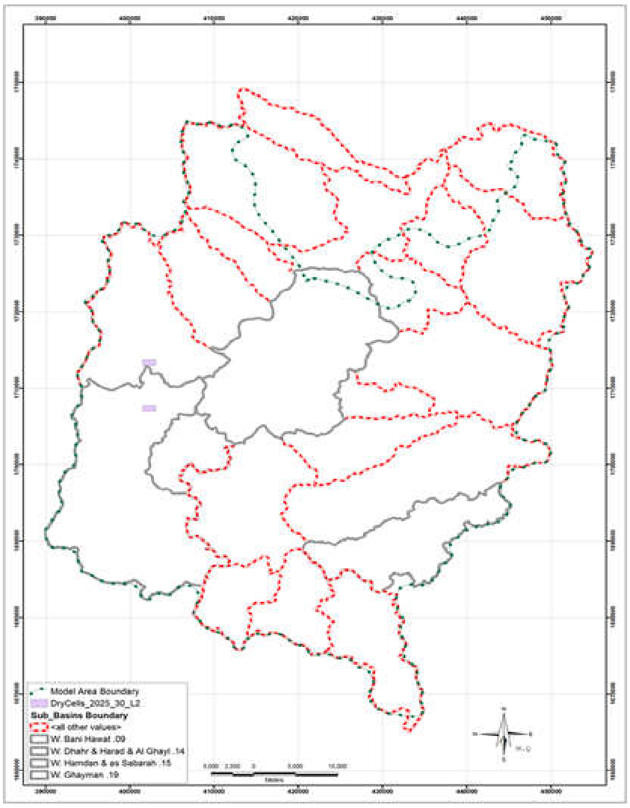

Figure (10): Expected Over- Exploitation Area in Second Layer for the Year 2025 (Scenario2)

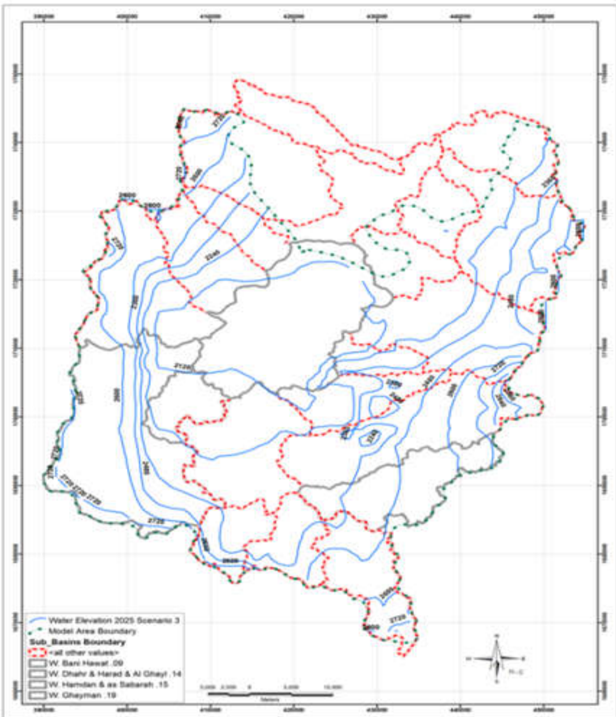

Figure (11): Water Table Elevation Contour in First Layer f or the Year 2025 (Scenario3)

Simulation results of the third scenario, in which the annual rate of pumping in the four targeted sub-basin will be 110.75 Mm^3/year if rate decreases to 50% and still the same to 2025 together with an efficient intervention related to (change land use, change crop pattern, value chain, marketing, modern irrigation techniques, water harvesting techniques, etc) evaluate complete water balance components for each of sub-basin budget zones ,water table elevation contour map was constructed (see Figure 11) and the over-exploitation areas, where the groundwater level has dropped dramatically, and the water formations have dried in these locations (Figure 12) for layer 1. Comparing the over-exploitation areas for the first simulated layer, (Figure 12) for scenario 3, with the over-exploitation areas (Figure 6 and Figure 7) for scenario 1, 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%.

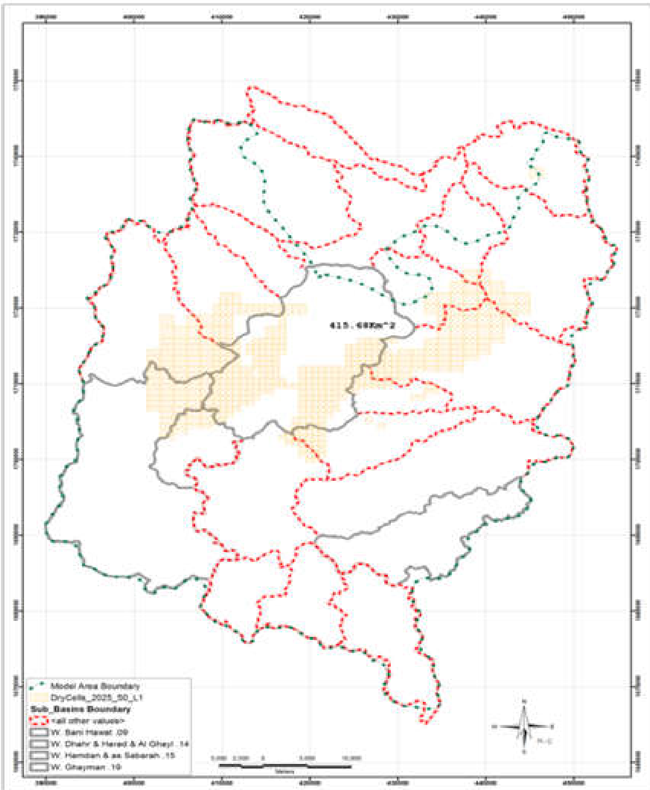

Figure (12): Expected Over-Exploitation Area Map for the Year 2025 (Scenario 3)

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.

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 (Km^2)		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

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.

Recommendation:

- 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, an 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.
- 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 the use of the mathematical model technique is not only for planning, but also for the 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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استخدام نمذجة المياة الجوفية (مودفلو) أداة إدارية للأحواض الفرعية المستهدفة في حوض صنعاء

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صالح الظبي　　عبدالله سيف

الملخص

قد برزت النمذجة العددية (مودفلو (MODFLOW أداة فعالة لإدارة موارد المياه الجوفية والتنبؤ بالاستجابات في المستقبل، وخاصة عند التعامل مع أنظمة طبقات المياه الجوفية المعقدة والتراكيب غير المتجانسة. تم استخدام نموذج مودفلو هنا أداة إدارية للأحواض الفرعية المستهدفة (حوض وادي بني حوات ، حوض وادي ظهر والغيل الفرعي ، حوض وادي حمدان والصبرة الفرعي)، أهم مصادر المياه الجوفية للقطاعات المحلية والزراعية في حوض صنعاء. قد تجاوز بالفعل استخراج المياه الجوفية من هذا الحوض العائد المأمون للمخزون الجوفي مما أدى إنخفاضا حادا في منسوب المياه وجفافا لمعظم الآبار. ويعمل حاليا أكثر من 13000 بئر بما في ذلك الآبار الحكومية والخاصة وغير المصرح بها داخل حدود الحوض. 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 إجمالي القيم لاستخراج المياه الجوفية بعد تصفية البيانات المتاحة، بما في ذلك بيانات الآبار الصادرة عن الهيئة العامة للموارد المائية–حوض صنعاء NWRA-SBلعام 2015. تم توثيق هذه البيانات في قاعدة بيانات وتخزينها في نسخة إلكترونية (إكسل .(Excel في هذه الدراسة، تم المحاكاة لثلاثة سيناريوهات مختلفة في تنمية المياه الجوفية. السيناريو الأول تم لتقويم الوضع الحالي حتى عام 2025. تركز السيناريو الثاني والسيناريو الثالث على تأثير زيادة المياه أي تقليل المعدل الحالي لاستخراج المياه الجوفية إلى 30٪ و 50٪ على التوالي، مع الأخذ بعين الاعتبار التدخل العالي لإدارة متكاملة للموارد المائية في حوض صنعاء المتعلقة بتغيير استخدام الأراضي، تغيير نمط المحاصيل، التسويق، تقنيات الري الحديثة، تقنيات حصاد المياه، إلخ ... يعطي السيناريو الثالث تحسناً ملحوظا في نظام الموارد المائية في الأحواض الفرعية الأربعة خلال فترة معقولة (في عام 2025)، ومن ثم سيحافظ على استدامة موارد المياه. ويوصي بتحسين نظم الري باستخدام طرائق حصاد المياه للحد من الخسائر وزيادة تغذية المياه الجوفية على التوالي في أربعة الأحواض الفرعية المستهدفة.

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