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Modeling of the Aleppo City Basin

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Postgraduate Studies (PhD)

Abstract: ***Groundwater is the main source of drinking and irrigation water in most arid and semi-arid countries. In such environments, management of water resources is the key challenge for sustainable development projects. During the years of war, Aleppo city suffered from repeated water outages from its main source, the pumping station in Khafsa on the Euphrates River. This prompted the Ministry of Water Resources to find urgent and emergency solutions to ensure water access for residents. The first phase involved drilling 150 emergency wells in the western parts of Aleppo, followed by a second phase where 51 additional wells were drilled to integrate them into the emergency plan. In this study, we mapped the wells and linked them to the Syrian stereographic network using GIS software, relying on the Syrian geological map, which was aligned with geological cross-sections of the study area to display well locations within the city. We then examined the hydrogeological conditions of the well-drilling areas by creating hydrogeological cross-sections using RockWorks17 software, enabling us to establish the geological model of the studied region. All data related to the wells exploited in the study area were compiled and documented based on individual pumping test reports for each well. We monitored periodic measurements of water levels in the studied wells from mid-2016 to the present. Finally, we used ModFlow software to create hydrographs of groundwater levels for wells with continuous periodic measurements.***

Keywords: 3-D geological model, Emergency wells, Groundwater reservoir, MODFLOW, RockWorks

1.Introduction

Aleppo City has faced a severe water crisis in recent years due to conflicts near water sources and related infrastructure, which led to damage and destruction. This prompted the **Ministry of Water Resources** to take urgent measures to alleviate the suffering of citizens by:

- Developing a **rapid relief plan** to secure alternative water sources in the city.
- Drilling **150 emergency wells** distributed across different parts of the city [1].

At a later stage, the **Water Institution**, in coordination with the **Directorate of Water Resources**, worked on drilling **an additional 51 wells** to be integrated into the alternative emergency plan [1]. To benefit from past hardships and the suffering endured by the citizens of **Aleppo,** and as part of a long-term strategic plan, the institution, in collaboration with the **Ministry of Water Resources**, has developed a strategy aimed at collecting water from the drilled wells into storage reservoirs currently being constructed in **Aleppo City**. This initiative seeks to provide water to residents, improve the city's water situation, and secure alternative water sources in cases of **emergencies and crises**. The figure (1) shows the locations of the collection reservoirs for the emergency plan wells and the contingency plan wells.

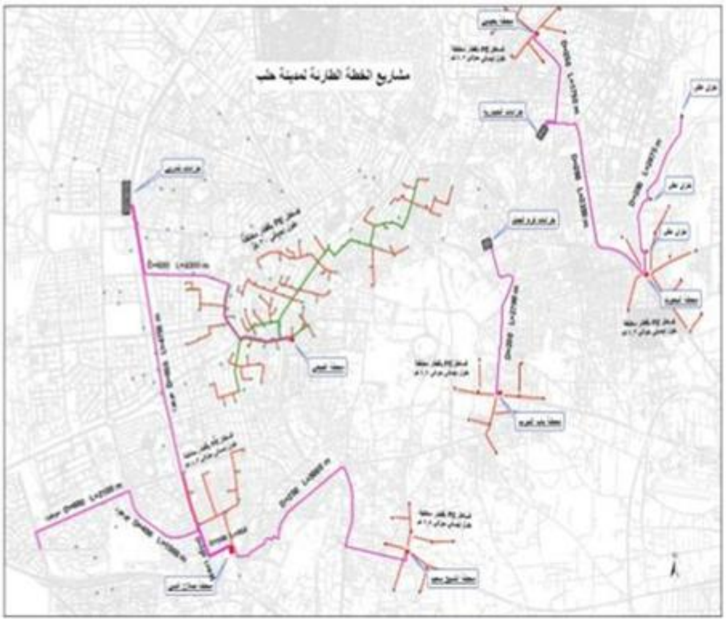


Figure 1: Locations of the collection reservoirs for the emergency plan wells and the contingency plan wells

1) Characteristic of the Study Area:

Aleppo City is located in **northwestern Syria** within the following reference coordinates [2]:

Xmin = -185600 Xmax = -174200
Ymin = 2200000 Ymax = 228400
Zmin = 130 m Zmax = 470 m

The depths of the **studied wells** range between **150 to 400 meters**, penetrating:

- The **first aquifer** (**Quaternary and Neogene**).
- The **second aquifer** (**Paleogene**).

There are **no wells** within the **third aquifer**, as reaching the **Cretaceous aquifer** requires drilling to a depth **exceeding 600 meters**, which is **not included** in the **emergency plan**. The figure (2) shows the general location of the wells within the city.

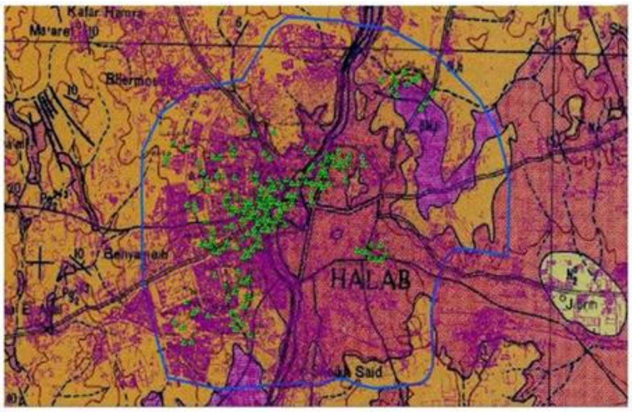


Figure 2: The general location of the wells within the city.

2) Research Justification:

Due to the **water crisis** experienced by **Aleppo City** as a result of **water supply interruptions** from the **Khafsa and Babiri pumping stations** on the **Euphrates River**, along with the **drilling of emergency wells** and **unregulated excessive groundwater extraction**, it became necessary to study the **scientific management** of well utilization through:

- Assessing the efficiency of these wells.
- Identifying the reasons why some wells went out of service.
- Explaining the irregular behavior of certain wells.
- Addressing the lack of a clear water pumping program to ensure optimal well utilization.
- Filling the gap in hydrogeological studies on Aleppo's groundwater reserves.
- Developing a mathematical model to
- Illustrate the mechanism for compensating extracted water losses in Aleppo.

Thus, the idea of conducting a comprehensive study emerged, aiming to preserve Aleppo's groundwater reserves from depletion and to achieve optimal groundwater extraction without harming the available water resources.

3) Research Review:

A review of previous reference studies on the Aleppo Basin focused primarily on geological and hydrogeological studies. The hydrogeological formations containing water-bearing layers in the studied area were classified into two groups: Neogene-aged water- bearing deposits, Paleogene-aged water-bearing depositsit is important to note that some wells penetrate more than one aquifer, as the studied area consists of multiple hydrogeological formations, each containing two or more water-bearing levels [3]. The figure (3) shows the the location of the Aleppo Basin on the water basins map in Syria.

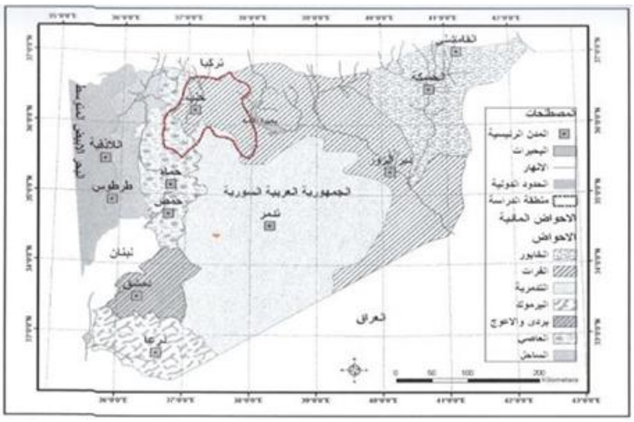


Figure 3: The location of the Aleppo Basin on the water basins map in Syria

4) Geological Setting:

The geology of Aleppo basin is described by several reports and geological maps. The most recent geological survey was conducted by Soviet experts of Selkhozprom export (1979) [4] under the general guidance of V.P. Ponikarov, including hydrogeological and hydrological investigations in different areas of Syria. According to this geological survey the geological base map was constructed at a scale of 1:200, 000. The geological map shown in Figure (4) was considered the foundation for developing various plans and thematic maps for this study.

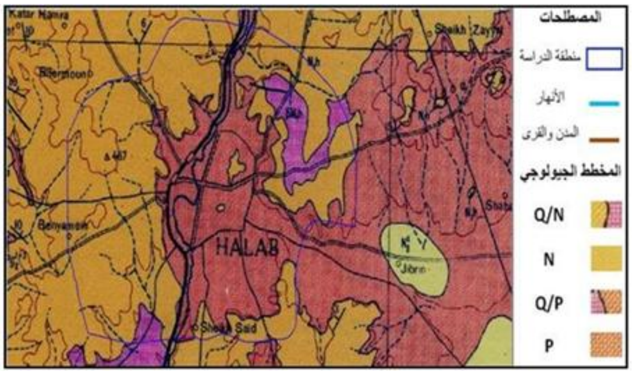


Figure 4: The general schematic of the geological structure in the studied area

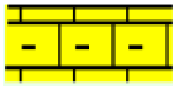
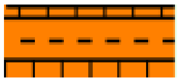
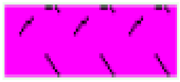
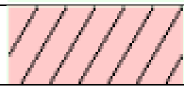
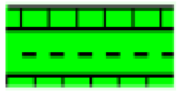
5) Materials and methods:

This research study is the first of its kind in **Aleppo City**, where the following objectives were pursued:

5.1 Creating lithological sections for emergency wells using RockWorks:

Groundwater resource management requires adequate information about the geological frameworks and hydrogeological system of the modeled region. These include a detailed description of the lithology and stratigraphic units based on the drilling results of the wells implemented within the emergency plan inside **Aleppo City**. These were stored in the Lithological Types table [3] in the RockWorks database. The table includes detailed information about rock material, pattern, color, and order in the model from the top to the base. Table (1)

Table 1: The lithological types of the study area

Layer No	Layer Name	Age	Lithological units	Stratigraphic Pattern
1	Pebbles, loams, gypsum, and salty clays	Quaternary sediments	Soil, loams, gypsum, and salty clays, and soil with gravel and pebbles.	
2	Limestone, conglomerates	Helvetian	Hardlimestone, shellylimestone, sandylimestone, massive limestone, conglomerates, marly limestone, and clayey marl.	
3	Limestone, clayey lime-stone, and flints	Neogene	Clay, basaltic tuff, sandy clay, clay limestone and gray limestone	
4	Basalt	Helvetian	Basalt, clay basalt, green basalt, volcanic tuff, basaltic tuff, black basalt, disintegrated basalt, porphyritic basalt and multy color basalt.	
5	Nummulite limestone	Paleogene	White nummulite limestone and nummulite limestone.	
6	Marls	Neogene, Paleogene	Marl, marl alternating between light to dark carbonate, oily marl, glauconitic marl, multy color marl, clayey marl, dolomitic marl and carbonate marl.	

We used the **RockWorks** [5] **software** by inputting the layers composing each well based on drilling data. This software allows us to enter all available information about the studied wells and enables integration with other programs. The software visualizes the wells according to their lithological description - Figure (5).

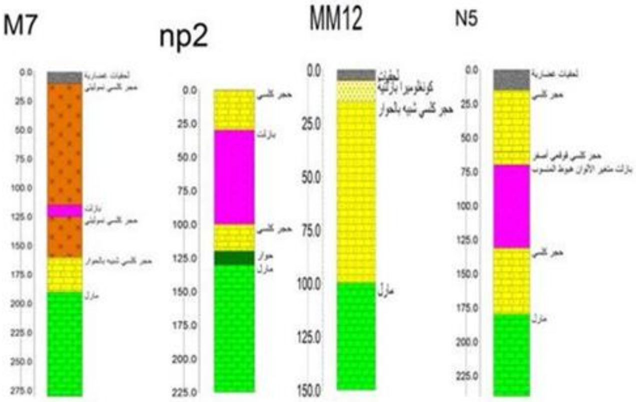


Figure 5: Lithological description of some studied wells in Aleppo City

It was found through these sections that the first aquifer belongs to the Quaternary age and is located in the course of the Queiq River (riverbed). Meanwhile, the third aquifer belongs to the Paleogene age and is exposed in areas farther from the river, especially in the eastern parts of the city. The second aquifer, from the Neogene age, is exposed in the western parts of the city, with some Neogene outcrops appearing in the elevated areas of the city, such as the AL-Ezaah town and Hanano Barracks.

5.2 3-D geological model:

After inputting the layers composing each well according to the lithological description of the rock fragments into the software, we were able to derive the 3D geological model of the studied area by automatically correlating the matching layers.

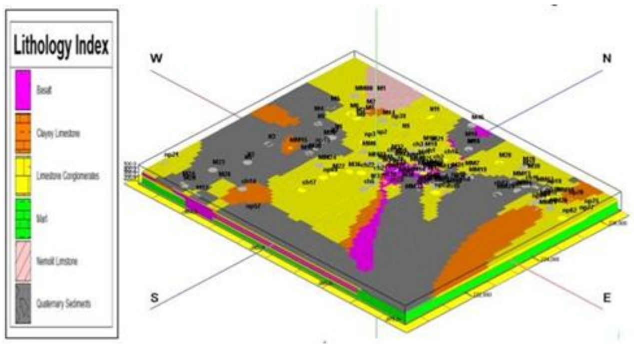


Figure 6: Lithological description of some studied wells in Aleppo City

From the 3D model, we conclude that most of the wells in the western part of the city are located on the Neogene aquifer, specifically within the Middle Miocene (Helvetian) and Pliocene.

5.3 Monthly groundwater observation data:

A database of water points was built in the study area. To understand the hydrodynamics of the aquifers in the studied area under the influence of well extraction, we prepared a well information database that includes various available data on periodic groundwater level readings. These readings are used for graphical representation of periodic monitoring data. The table (2) presents Coordinates, well position, total depth, and monthly groundwater observation data cover the middle of 2016 year according to the ground surface elevation, recorded by the General Directorate of Water Resources in Aleppo.

Table 2: Piezometric measurements of emergency plan wells during the year 2016

Borehole name	Coordinates		Depth	Pump level	2016												Location
	X	Y			1	2	3	4	5	6	7	8	9	10	11	12	
Ch-7	- 180483.07	224517.52	218	12								7.9	7.57	7.5	7.24	7.24	Opposite the Directorate of Education
Ch-9	- 182052.15	224395.75	222	57								5.15	4.64	54.4	4.42	4.41	Al-Qusour Street.
Ch-12	- 179408.24	225583.23	200	5								4.75	4.75	4.77	4.7	4.58	Al-Villat Street.
MM-29	- 183376.67	224124.64	300	100								-	80.3	80.4	80.1	80	New Aleppo Town
Np-18	- 179471.58	225235.78	204	5								5.1	5.05	5.04	4.7	4.56	Youth Welfare District in Aleppo

After collecting and documenting all data related to the wells utilized in the study area, based on individual well pumping test records, we created hydrographs of groundwater levels for wells with continuous periodic measurements - figure (7, 8, 9).

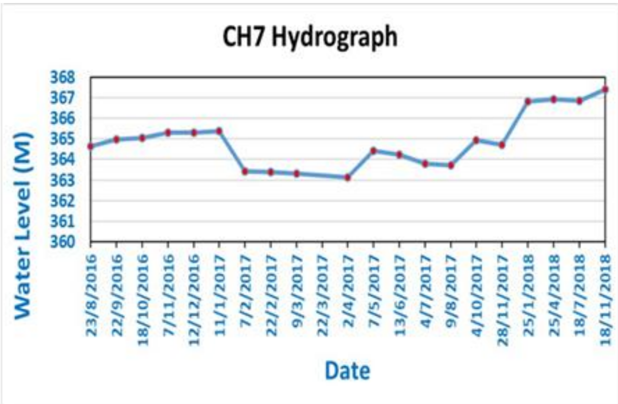


Figure 7: Borehole Ch-7 located Opposite the Directorate of Education.

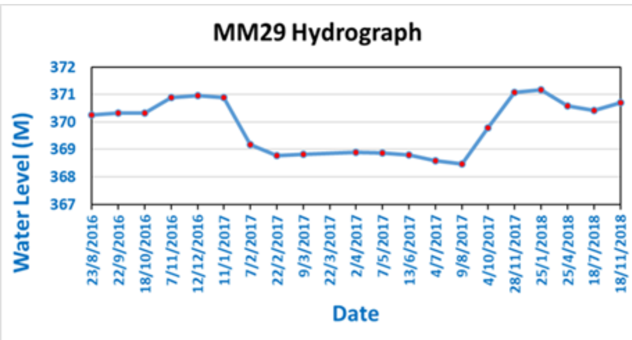


Figure 8: Borehole MM-29 located New Aleppo Town

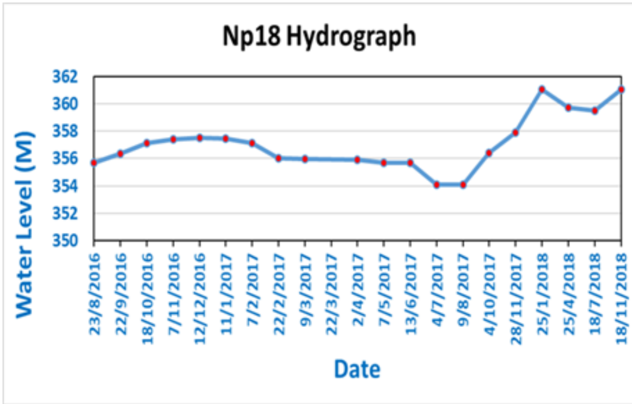


Figure 9: Borehole Np-18 located in Youth Welfare District in Aleppo

From the previous figures, we observe that when the effects of wells overlap in a certain area, the piezometric level of those wells becomes very similar, behaving as if they were a single well. This indicates uniformity in the hydraulic properties of the aquifer, which results in the same behavior for those wells. When nearby wells are operated together, their drawdown cones overlap and interact, affecting the shared drawdown cone and discharge. Most of these wells show a decline in the drawdown cone due to excessive extraction.

5.4 Integrating RockWorks with the Geographic Information System GIS:

Depend on water information database, we integrated GIS with RockWorks and Excel. Through this system, we were able to draw groundwater contour lines to determine the general trend of groundwater movement over different periods. It was observed that the water table fluctuated significantly in the low-lying areas of the city center, while wells in the western parts of the city maintained higher levels even under intense pumping conditions - figure (10).

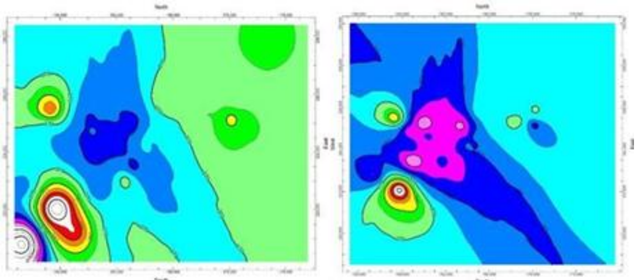


Figure 10: W.L between 4/7/2017 and 25/4/2018.

5.5 Model Design (Input Parameters):

Ground-water modeling has become an important methodology in support of the planning and decision-making processes involved in ground-water management. Ground-water models provide an analytical framework for obtaining an understanding of the mechanisms and controls of ground-water systems and the processes that influence their quality, especially those caused by human intervention in such systems [6]. Based on the above, the length and width of the model area were determined 15.4Km, 14.5 Km, and the cells of the mathematical model are characterized by the following properties, as illustrated in the two figures (7, 9).

- **Total number of cells:** 899 cells.
- **Number of hydrogeological layers:** 2 layers.
- **Cell dimensions:** 0.5 Km × 0.5 Km.

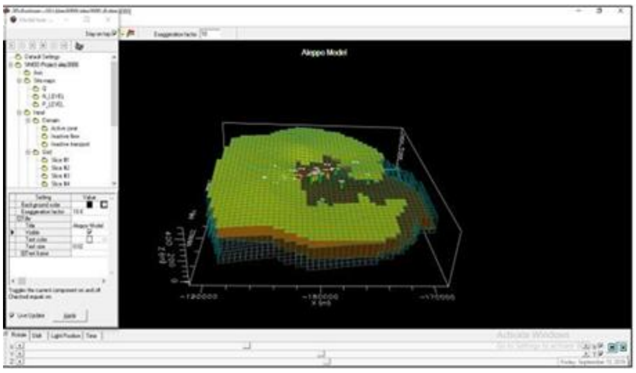


Figure 9: 3D hydrogeological model of the studied area.

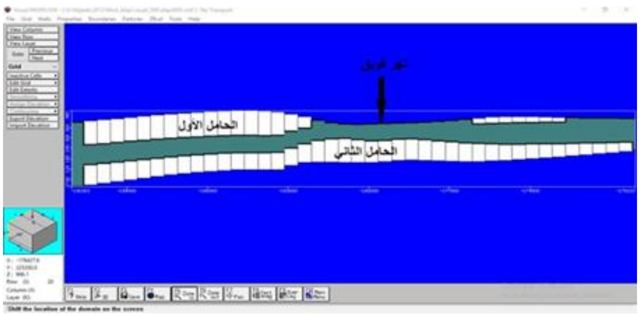


Figure 10: The hydrogeological layers in the model of Aleppo city.

5.6 Modelling Software Selection:

After hydrogeological characterization of the site has been completed and the conceptual model developed, a computer model software is selected. The selected model should be capable of simulating conditions encountered at a site. In this research we adopted ModFlow software [7]. MODFLOW-based ground-water flow model. The USGS 3-D Finite-Difference Ground-Water Flow Model- figure (11).

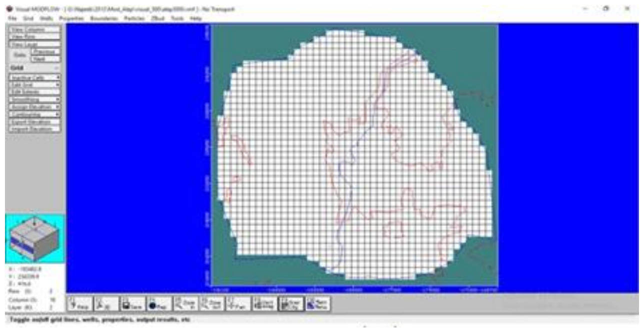


Figure 11: Groundwater model for studied area.

5.7 Boundary Conditions:

A calibrated model uses selected values of hydrogeologic parameters, sources and boundary conditions to match historical field conditions. The process of model verification may result in further calibration. After the model has uccessfully reproduced measured changes in field conditions, it is ready for predictive simulations. Using the principles of trial and error, the mathematical model was calibrated until the absolute mean value of the differences between the groundwater levels calculated by the model and the measured values in nature at the calibration points reached the closest possible match. The calibration was carried out by adjusting the transmissivity (T) values of the aquifer layers, the hydraulic boundaries of the model, the infiltration rate from rainfall, permeability coefficient values, and storage coefficient values. By applying the trial-and-error method, all errors were corrected in accordance with the available information about the studied area and the results obtained from the model- figure (12).

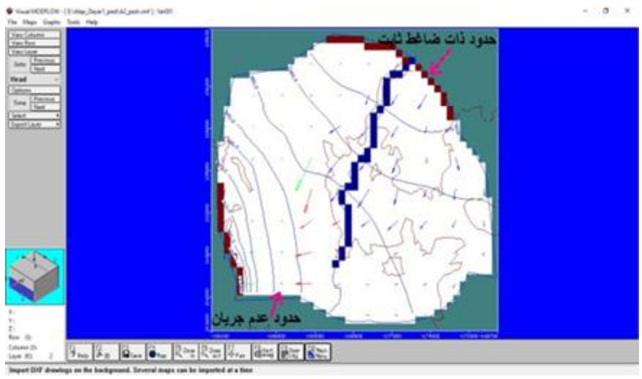


Figure 12: Boundary Conditions of Ground-Water Model

2.Result and Discussion

2.1 Model Verification:

The calibration process was carried out in two stages:

The first stage represents the steady-state condition of the aquifer, where groundwater levels are assumed to be stable at a specific moment. During this stage, the boundary conditions of the mathematical model and the permeability coefficient values were reviewed and calibrated. The second stage represents the transient condition of the aquifer (the dynamic state) due to changes in water components over time. During this stage, infiltration values from rainfall and storage coefficient values were reviewed and adjusted- figure (13).

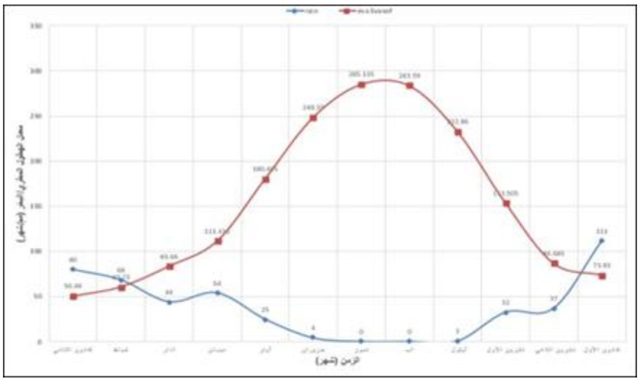


Figure 13: Monthly average rainfall and evaporation for the years 2016, 2017, 2018 at Aleppo station.

The previous figure, it is evident that the evaporation component exceeds rainfall in all months except January, February, and December, where the rainfall rate surpasses the evaporation rate. From this, it is clear that groundwater recharge in the study area is minimal due to the significant difference between rainfall and evaporation values, as well as the extreme variation in precipitation between winter and summer months. During the period of no rainfall, we conclude that the infiltration volume is almost negligible and does not exceed 2% of the difference between rainfall and evaporation. The calculated groundwater levels were also compared with the invested values in the observed wells of the first and second aquifers- figure (14, 15).

2.2 Mathematical model calibration (observed, calculated values):

The calibration results indicate that the infiltration rate from rainfall is very low throughout the year and did not affect the model calibration when comparing the groundwater levels calculated by the model with field measurements.

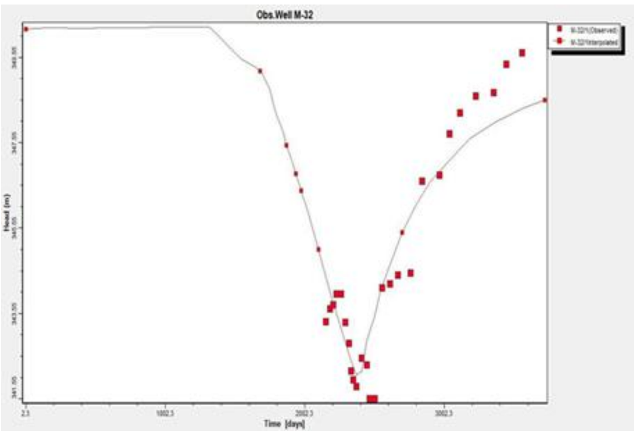


Figure 14: The calculated and observed (W.L) for a well in the first aquifer

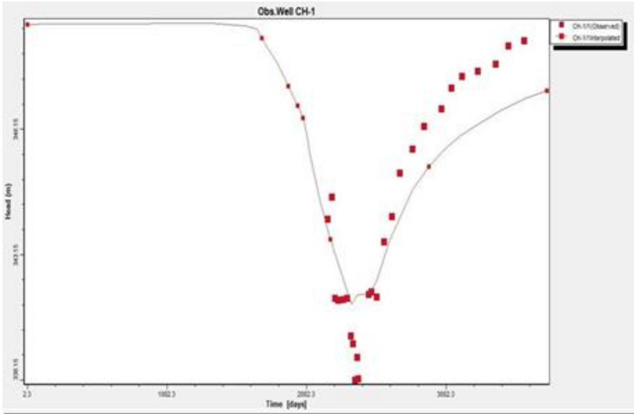


Figure 15: The calculated and observed (W.L) for a well in the second aquifer

These figures show that despite the deficiency in storage coefficient values, there is an acceptable agreement between the model results and most field measurements. It should be noted that achieving complete agreement is not possible due to the lack of continuous and frequent values for well withdrawal rates based on actual daily operation throughout the month. The significant deviation between invested and calculated values at certain time periods is attributed to measuring groundwater levels inside production wells while they are in operation, without considering the drawdown caused by well losses.

2.3 Groundwater flow and Budget:

To calculate the components of the water budget in the static state, the garden wells in the city were relied upon to determine the extracted water volumes before the emergency wells were drilled. Additionally, the wells that were operated and utilized were considered, and the daily operating hours were determined in the dynamic model to assess the extracted water volumes over successive periods after the emergency wells were drilled in the city. The figures (16, 17, 18, 19, 20, 21) illustrate the quantitative estimation of the water budget components for the Neogene and Paleogene aquifers between January 2016 to the end of December 2018.

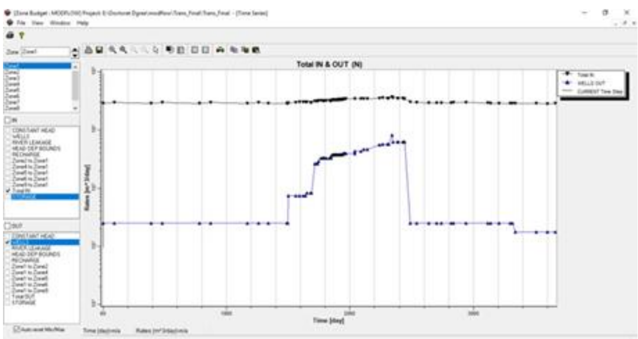


Figure 16: Daily average well investments and groundwater imports from the east and south for the Neogene aquifer during the period 2016-2018

It is evident that the rate of groundwater imports has increased due to the high investments in emergency wells, which has led to a decline in water levels and an increase in the hydraulic gradient.

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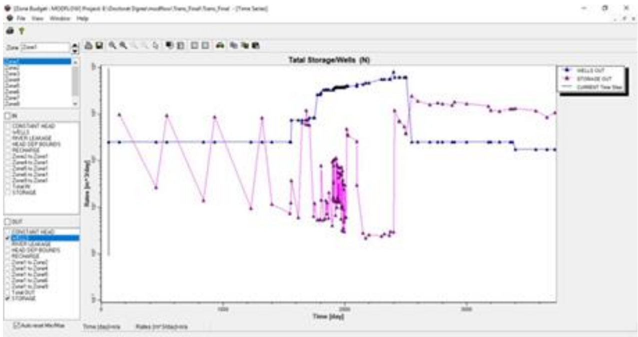

Figure 17: Daily average well investments and extracted groundwater storage for the Neogene aquifer in Aleppo city during the period 2016-2018

From the previous figure, it is evident that approximately 40% of the investments in emergency wells are being depleted from the groundwater storage.

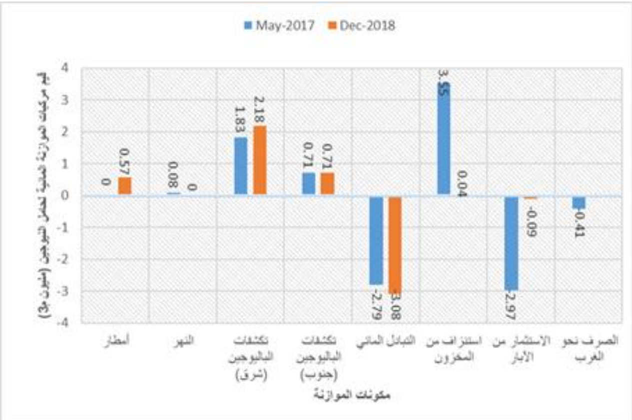

Figure 18: Graphical representation of the water budget values for the first aquifer (Neogene) during the period 2016-2018

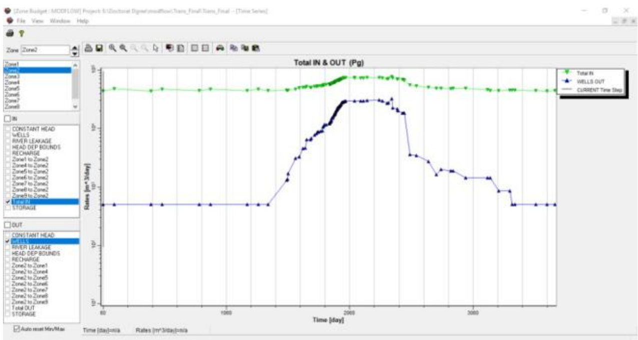

Figure 19: Daily average well investments and groundwater imports from northeastern boundary of the Paleogene aquifer during the period 2016 - 2018

The results indicate that the increase in groundwater flow rate from the eastern and southern boundaries is due to the high investments in emergency wells, which has led to a decline in water levels and an increase in the hydraulic gradient as a result of continuous depletion of groundwater storage.

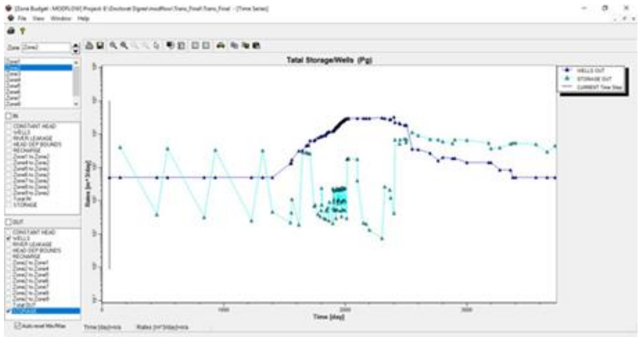

Figure 20: Daily average well investments and extracted groundwater storage for the Paleogene aquifer in Aleppo city during the period 2016 - 2018.

We notice that whenever groundwater is extracted from the second aquifer through the investment wells spread across the city, groundwater levels decrease, leading to the depletion of groundwater storage.

Figure 21: Graphical representation of the water budget values for the second aquifer (Paleogene) during the period 2016 - 2018

We notice that the intense groundwater extraction in 2017 corresponds with significant depletion of groundwater storage. With the cessation of emergency wells in 2018, the depletion dropped to its lowest value.

3.Conclusions and Recommendations

The model was operated under several proposed scenarios, through which we were able to establish a safe investment system based on the results of running the mathematical model for both steady and unsteady states regarding the aquifers in the city.
It was concluded that the number of wells drilled in the emergency plan was excessively high, leading to financial resource waste and disruption in the behavior of the groundwater reservoir due to the proximity of the wells to each other. A more in-depth hydrogeological study would have been preferable to determine well drilling locations based on seismic, geophysical, or electromagnetic surveys.

Additionally, the withdrawal of some agricultural lands surrounding the city from investment and the cessation of groundwater extraction contributed to the partial refilling of depletion cones, helping the groundwater reservoir recover some of what was lost in previous years.

The mathematical model presented in this research can be relied upon to establish a safe operational and investment system for wells in the future. It can also predict potential changes resulting from water investments in the city. This model allows for managing withdrawal operations within Aleppo, regulating the volume of water permitted for extraction by monitoring groundwater levels over time.

This enables the official entities responsible for the city's water sector to develop alternative plans by linking the drilled wells within a structured plan to collective reservoirs, where water can be gathered and pumped into Tishreen reservoirs, ensuring the continuity of water supply in the city during crises and emergencies.

Acknowledgments

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