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Bathymetric Map Production of Therthar Depression Basin and Water Storage Volume Estimation

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ABSTRACT

Water crisis, drought, and desertification are prominent environmental issues facing many countries and threaten their sustainable development. Therthar depression basin in Iraq was selected as a study area. A new approach was adapted in producing a bathymetric map by merging contours derived from both topographic maps and digital elevation models using ArcGIS applications. Water storage volumes were estimated from 2017 to the end of 2023 using the trapezoidal rule. The results demonstrate that the maximum water storage volume was 80% of the total storage capacity in 2019. In 2021, this percent began to decrease significantly as a result of climatic changes until reached a dead storage about 40% in 2023. Large surface area of Therthar depression leads to increased evaporation and infiltration rates. The water consumption exceeded the incoming water storage by 5.292 billion cubic meters (bcm) in May and 13.127 bcm in October, between 2017 and 2023. The comparison between the estimated and actual live storage volumes resulted a root mean square error of 0.534 m and a coefficient of determination (R^2) equals 0.871. However, to award off flood risks in rainy years, the study proposes increasing Therthar depression design elevation to 67 m rather than 65 m in proportion to Therthar arranger gate level.

1. Introduction

Obvious alterations have occurred in many lakes and depression basins in the world during the last years as a result of man-made activities and climatic changes. These changes cause multiple environmental issues that stymie sustainable development. Remote sensing images, topographic maps, bathymetry, and Digital Elevation Models (DEMs) are necessary data for water storage volume estimation using Geographic Information System (GIS). Currently, ArcGIS tools and free download open source DEMs are effective for contouring, surface areas, and volume calculation. Satellite internet is an important service supplying approximately worldwide coverage [1]. Shuttle Radar Topography Mission (SRTM) maps the world on a 3-dimentional surface and produces DEMs at a resolution of 30 m commonly [2].

The bathymetric maps in developing countries are scarce due to the expensive fieldwork requirements [3]. Also, the global information on lake water storage volumes are limited in obtainability, insufficiently documented, and changeable [4, 5]. Bathymetry devices such as echo-sounder and sonar are required in site hydrographical surveys. Radar altimetry is frequently restricted by spatial and temporal resolution. Hence, multi altimeter data are needed to observe lake depths [6]. Some lakes are difficult to access due to security standpoint especially in Iraq like Therthar

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depression lake. Mosaicking the topographic maps of a lake site is considerable an appropriate solution for such problems.

Inflow and outflow variations determine water storage volume changes in lake basins. The inflow usually comprises rains, groundwater recharge, and surface runoff [7], while the outflow encompasses evaporation and infiltration mainly. Rainfalls constitute about 30% of water resources in Iraq, while the water quantities of rivers coming from neighbouring countries are estimated by 70% (General Authority of Dams and Reservoirs, Ministry of Water Resources in Iraq). Therthar depression basin is selected as a study area. The primary use of Therthar depression is to gather surplus water of Tigris River in flooding seasons, and to recharge Tigris and Euphrates rivers through the dry seasons. The annual change estimation studies of surface areas and storage capacity provide important lakes geodatabases especially when using GIS environment.

Numerous studies have been conducted concerning bathymetric maps, lake topography, surface areas, and water storage volumes. The high cost of traditional underwater field measurements makes the lake bathymetry limited availability [8, 9].

Sousa [10] provided extensive details about Therthar depression genesis, particularly the bottom, and mentioned that the depression comprises from two ravines. The bottom elevation of one of these ravines is 42 m above sea level while the other is about 3 m below sea level. Sissakian [11] examined topographic maps at a scale of (1:100000) and stated that the entire Therthar depression shows an elevation of (10 m) above sea level as the deepest area. The reason for this is the difficulty in distinguishing the depression deepest area as the result of scale accuracy limitations of these maps. Khalaf [12] modified ASTER DEMs that have a spatial resolution (90 m × 90 m) by gridding the topographic maps. This procedure allows to process DEM deficiency that represents the whole Therthar depression lake in one elevation of 44 m above sea level. Thus, the distinction between topographic, morphometric, and hydrological characteristics of the lake can be enabled. Hussain [13] observed the variations of surface areas and water storage capacities in Hamrin Lake between 2011and 2022. The results exhibited that the lake lost about 98 percent from its normal storage capacity in 2022. Ahmood et al. [14] reviewed many studies related with surface areas and storage volume changes in eight lakes in Iraq using remote sensing integrated with GIS.

Bastawesy et al. [15] outlined the variations in surface areas and water storage volumes in Tushka depression lakes, Egypt, using satellite images and topographic map DEMs between (2002) and (2006). At this period, the water deficiency annual rate was estimated to be 2.5 m in elevation. Consequently, overall surface areas and water storage volumes of these lakes were shrunk from (1591 km^2) to (937 km^2) and from 25.26 billion cubic meters (bcm) to 12.67 bcm, respectively. Asfaw et al. [16] simulated water storage fluctuations in Ziway lake (Ethiopia) from 2009 to 2018 using multisource satellite imagery, radar altimetry, and ground data. The study resulted in level agreement between satellite altimetry and ground observations by a coefficient of determination (R^2) equal to 0.920 and a Root Mean Square Error (RMSE) of 0.119 m. According to the study, the annual rates of levels, surface areas, and water storage volumes have all minimized by 0.04 m, 0.08 km^2, and 20.4 million cubic meters, respectively. Ziway lake has wasted 12.75 percent from its total storage capacity from 2009 until 2018. Xiao et al. [17] chose six lakes in Tibetan Plateau and guessed water depths and volumes by expanding the surrounding topography of a lake into the underwater region. The comparison between the guessed and measured depths of these lakes deduced a statistical model with mean R^2 equals 0.760.

Giambastiani et al. [18] measured depths using Sonar with Global Positioning System (GPS) and WiFi for multiple lake basins in Tuscany (Italy) then developed a volume estimation model with the aid of surface areas. The correlation between computed and actual volumes gave R^2 of 0.940. Ahmed [19] produced a bathymetric map by measuring (70000) sonar field points in Terkos lake (Turkey) and building GIS geodatabases. The shoreline was revealed by image classification.

The study drew the level, area and volume curve giving an image of the lake bathymetry.

Deposition and silt are the main issues impacting the lake basin storage capacity. Sedimentation is gradually reducing the storage capacity necessitating the sediment accumulation rate determination over time [20]. Ibrahim et al. [21] measured bathymetric and topographic data by Differential GPS Hi Target V 30 and echo-sounder for determining basin storage volumes of Tunga dam (Nigeria). The DEM was represented by Triangular Irregular Network (TIN) indicating that the deepest site is (21.25 m). The study suggested carrying out basin dredging in order to enhance the water storage capacity.

Drought and desertification are climate change phenomena that threaten water and food security in many countries. In 2023, most of lakes and marshes in Iraq began drying up one after the other, leaving only the dead storage in Therthar depression lake. The Ministry of Water Resources used pumps to withdrawal the dead storage from Therthar depression basin to feed Tigris and Euphrates rivers as a result of the lack of rains and water received from neighbouring countries in addition to a poor management. The use of a dead storage for the first time since the lake was constructed in 1950s last century is a worrisome indicator of how far the water crisis has aggravated. Increasing drought hazards demand that decision makers take urgent procedures ensuring water quotas arrival from neighbouring countries and limit the water excessive consumption. The knowledge of stored and consumed water quantities in lake basins over years is necessary for water usage regulation. In contrast to the other reviewed studies, this paper adopted a new approach in producing a bathymetric map by merging contours derived from both topographic maps and open source DEMs in ArcGIS environment. In addition, the water storage capacities were estimated using the trapezoidal rule for volumes. The new contribution is to estimate the excess quantities of water consumption over the water storage in Therthar depression basin during the period between 2017 and 2023. The study suggests enhancing the storage capacity of Therthar depression by increasing its maximum elevation.

2. Methodology

2.1 Study area

Therthar depression is 120 km northwest Baghdad city in the Jezira land between Stables ruins south Samarra on Tigris River and Hit stubble on Euphrates River. Therthar depression basin is selected as a study area bounded by latitudes 33° 25′ 30″ to 35° 00′ 00″ north and longitudes 42° 30′ 00″ to 44° 00′ 00″ east. It is the widest and deepest depression in Iraq that its bottom depth is 3 m below sea level and the bank level when full is 65 m above sea level. The depression surface area is estimated between 2500 km^2 to 2700 km^2 when full while its total storage capacity ranges from 85 bcm to 90 bcm [10]. The water loss quantity due to evaporation and absorption is directly proportional to the surface area and is estimated about 5 bcm per year when the depression basin is full [10, 22]. Therthar depression is used as water storage to stave off floods away from Baghdad city since 1956 by constructing Samarra and Therthar arrangers. Flood control needs to investigate the relationship between river courses adjacent or connected to the depression. Figure 1 shows Therthar depression basin location prepared by using google maps and ArcMap layout. Therthar depression lake has several structures displayed in Figure 2 and Table 1. Figure 2 has been prepared from google earth satellite images using ArcMap application. World Geodetic System (WGS) 1984 is the used coordinate system.

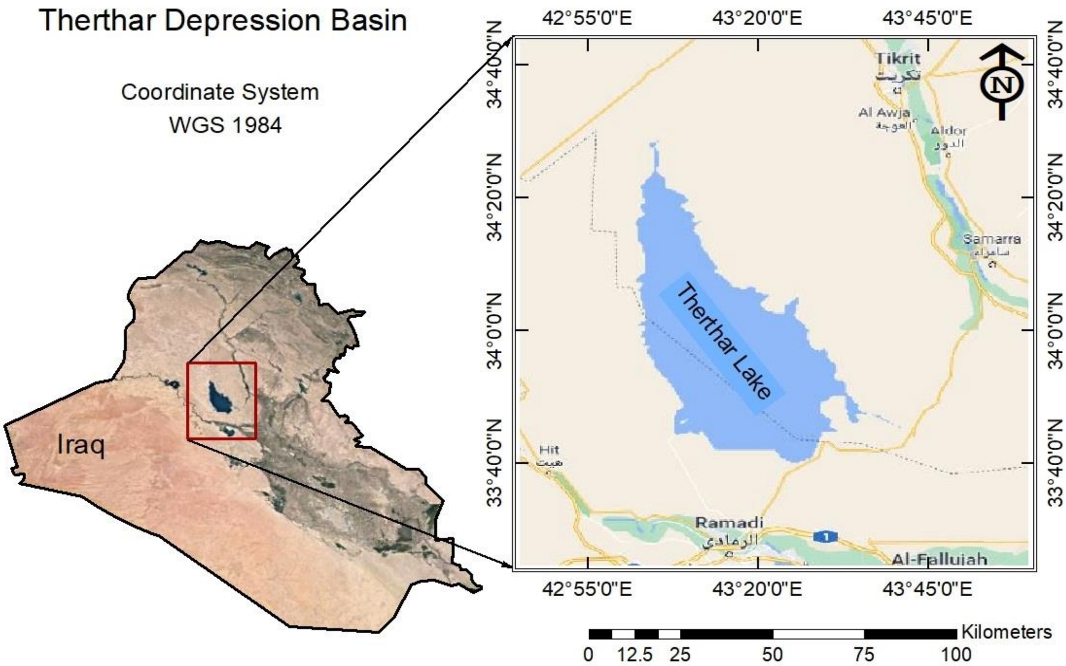


Figure 1. Therthar depression basin layout using Google maps and ArcGIS software

(a) Therthar and Samarra arrangers

(b) Main Therthar outlet arranger

(c) First partition arranger (Euphrates) and second partition arranger (Tigris)

(d) Al-Shalala arranger

Figure 2. Therthar depression lake arrangers

Table 1: Therthar depression lake structures (Ministry of Water Resources, Iraq)

Arranger	Construction Year	Gate Numbers	Gate Elevation (m)
Samarra arranger	1956	17	58 – 69
Therthar arranger	1956	34	63 – 69
Main Therthar outlet arranger	1976	6	40 – 65
First partition arranger (Euphrates)	1976	4	38.5 – 47
Second partition arranger (Tigris)	1981	4	40 – 47
Al-Shalala arranger	1981	4	37.15 – 45

2.2 Data and Applications

Both topographic maps and DEMs have been used to derive contour lines of Therthar depression. The topographic maps were obtained from Ministry of Water Resources, General Authority of Survey at a scale (1:100000) and contour interval of (5 m) produced in 2015, while DEMs were downloaded from SRTM tiles. Sentinel Hub EO Browser has been used to download multitemporal Sentinel images from 2017 to about the end of 2023. In each of these years, two images were downloaded: one in May (spring season) and the other in October (autumn season) because the maximum and minimum water flow in lakes happens in these months, respectively. The obtained data are listed in Table 2. ArcGIS Desktop 10.8 applications, ArcMap and ArcScene, have been used for data processing. Therthar depression location map and structures were prepared from google maps and google earth satellite images. Due to unavailability of reliable sources for live storage in Therthar depression basin, the water storage volumes mentioned in [10] are considered the more credible data because they were prepared by consulting companies reports. According to that, these data have been approved as real storage volumes assessing the estimated water storage volumes in this study.

Table 2: Data specifications and sources

Data	Specifications	Source
Topographic maps	Scale (1:100,000) Contour Interval 5 m	Ministry of Water Resources, General Authority of Survey
SRTM (N33E042, N33E043, N33E044, N34E042, N34E043, N34E044)	Resolution 30 m 1 arc second	NASA Earthdata https://dwtkns.com/srtm30m
Sentinel images	Resolution 10 m	https://apps.sentinel-hub.com/eo-browser

2.3 Data processing

The topographic maps, raster images, and DEMs have been processed in ArcGIS software. WGS 1984 is the coordinate system of these rasters. Project Raster Tool in ArcToolbox is implemented to convert the geographic coordinate WGS 1984 to WGS 1984 Universal Transverse Mercator (UTM) zone 38 north metric system for calculating lengths, areas and volumes. Using the Mosaic tool, nine topographic maps have been combined to produce the bathymetric contour map of Therthar depression basin. Also, the six tiles of DEMs are merged into one raster. The methodology of data processing is illustrated in Figure 3. Topographic maps and DEMs together were adopted for generating contours. Contour lines at intervals of one meter have been derived from DEM. Due to the density of contour lines at this interval and for compatibility with topographic map contour interval, the main contours have been drawn at a contour interval of 5 m in Figure 4. The open-source DEM generates contours up to 44 m. Other contours from 5 m to 40 m at intervals of 5 m have been digitized from topographic maps. Digitization process takes a long time compared by the direct DEM contouring using the Contour tool in Surface, Spatial Analyst Tools. Contours extracted from topographic maps and DEMs have been combined using the Merge tool in ArcMap.

The bathymetric map in Figure 4 shows the nine topographic map indexes employed in producing contours. The best contour fitting for the lake boundary of each satellite image has been assigned in ArcMap. Calculate Geometry tool in the layer attribute table was used to compute contour areas. Water storage volumes have been calculated using the trapezoidal rule for volumes (end areas) method as in Equation 1. The RMSE and R^2 have been evaluated by determining differences between calculated and actual storage volumes. Equation 2 is used to calculate RMSE.

$$\text{Volume} = \text{Height} \times \left(\frac{Area1 + Area2}{2}\right) \qquad (1)$$

$$RMSE = \frac{\sqrt{\sum(volume\ difference)^2}}{number\ of\ Observations} \qquad (2)$$

The depression floor elevations vary by their position differences and range between (– 3 m and 42 m) from sea level. The elevations in Therthar depression adopted in calculations are taken from the zero meter sea level neglecting depths below it due to sediment accumulation in the depression floor during its use as a water reservoir for more than half-century. According to these reasons, the water storage volumes are calculated from the sea level to achieve accurate estimations avoiding errors caused by the depression bottom irregularity. All calculations have been made based on the real contour lines derived from both topographic maps at scale (1:100000) and DEMs. The cumulative water storage volume for the required contour has obtained by calculating the volume between each two successive contours using the trapezoidal rule. Then, the resulted value is adding to the former volume computed from the sea level.

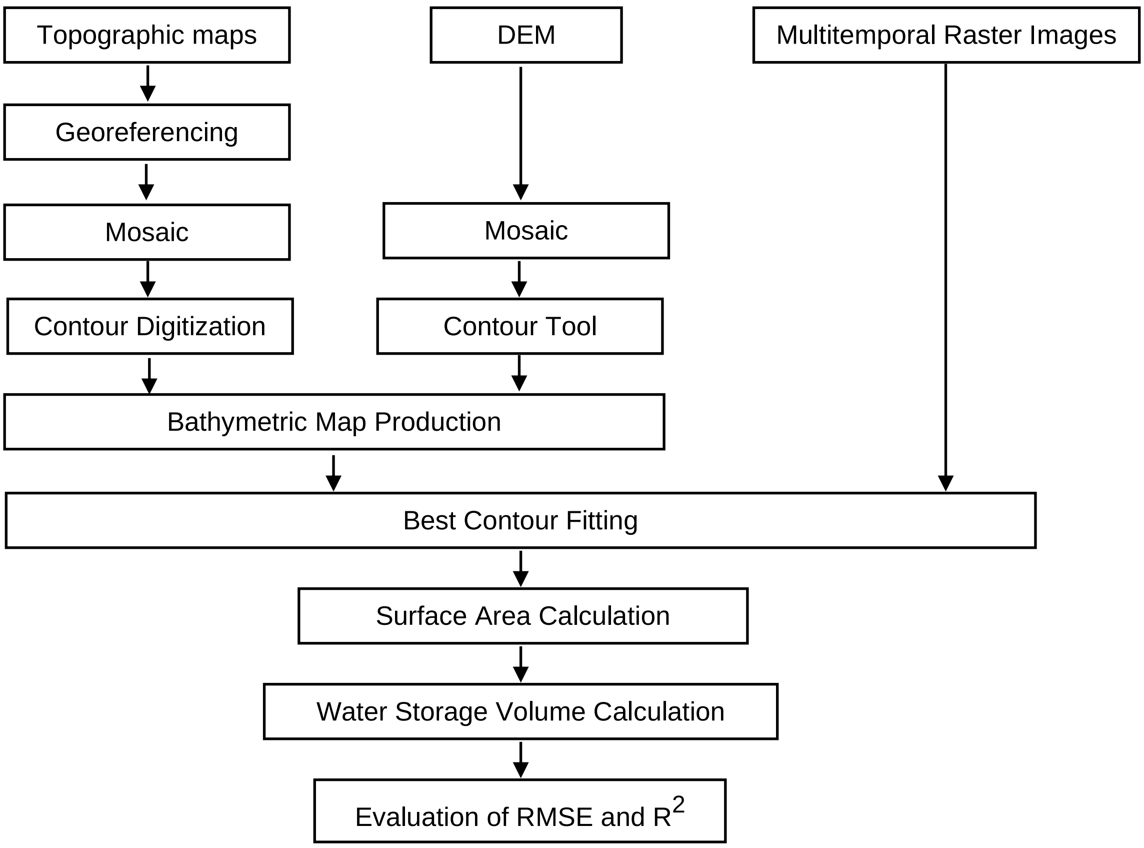
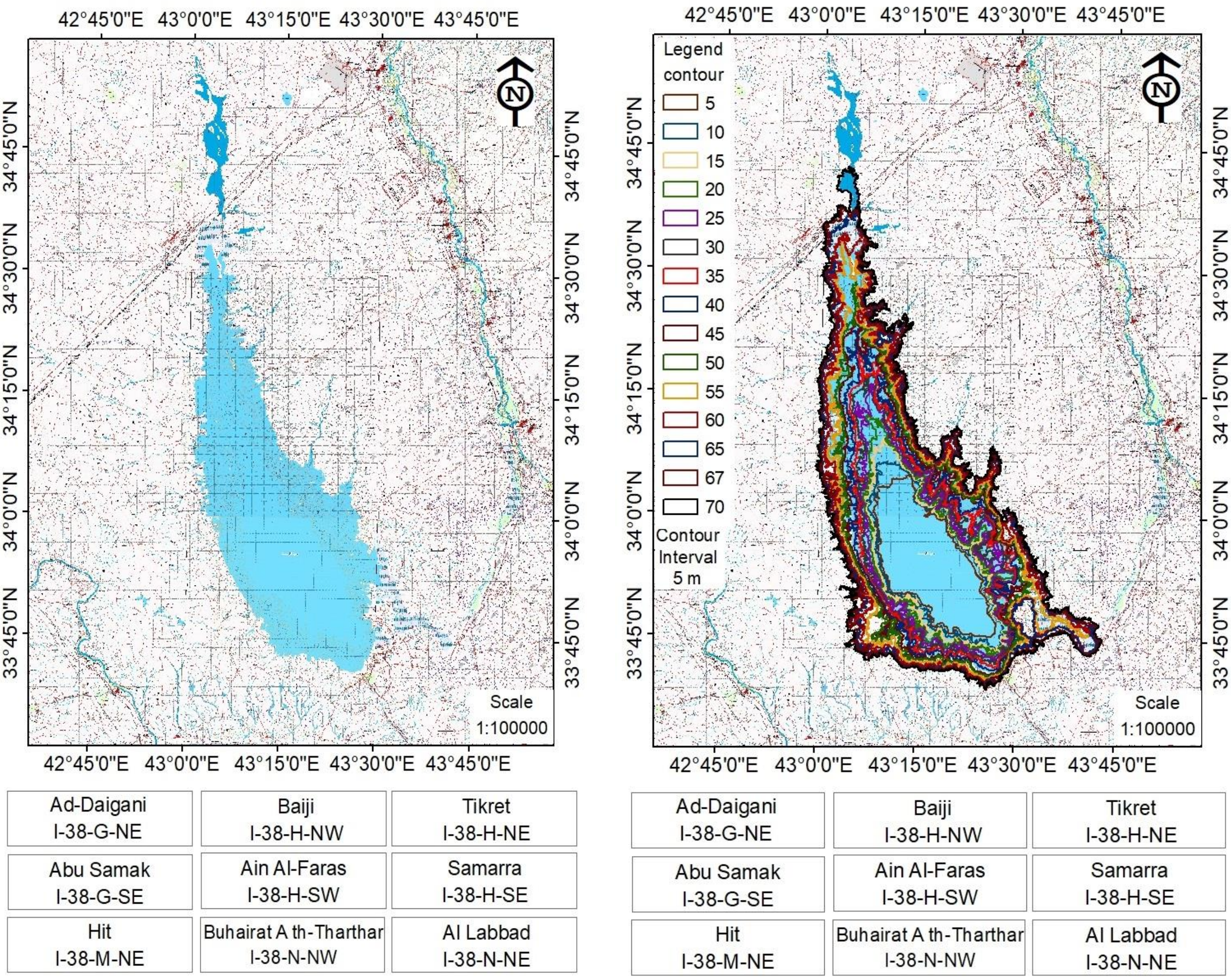


Figure 3. Data processing procedures



(a) Topographic Maps (b) Bathymetric Map

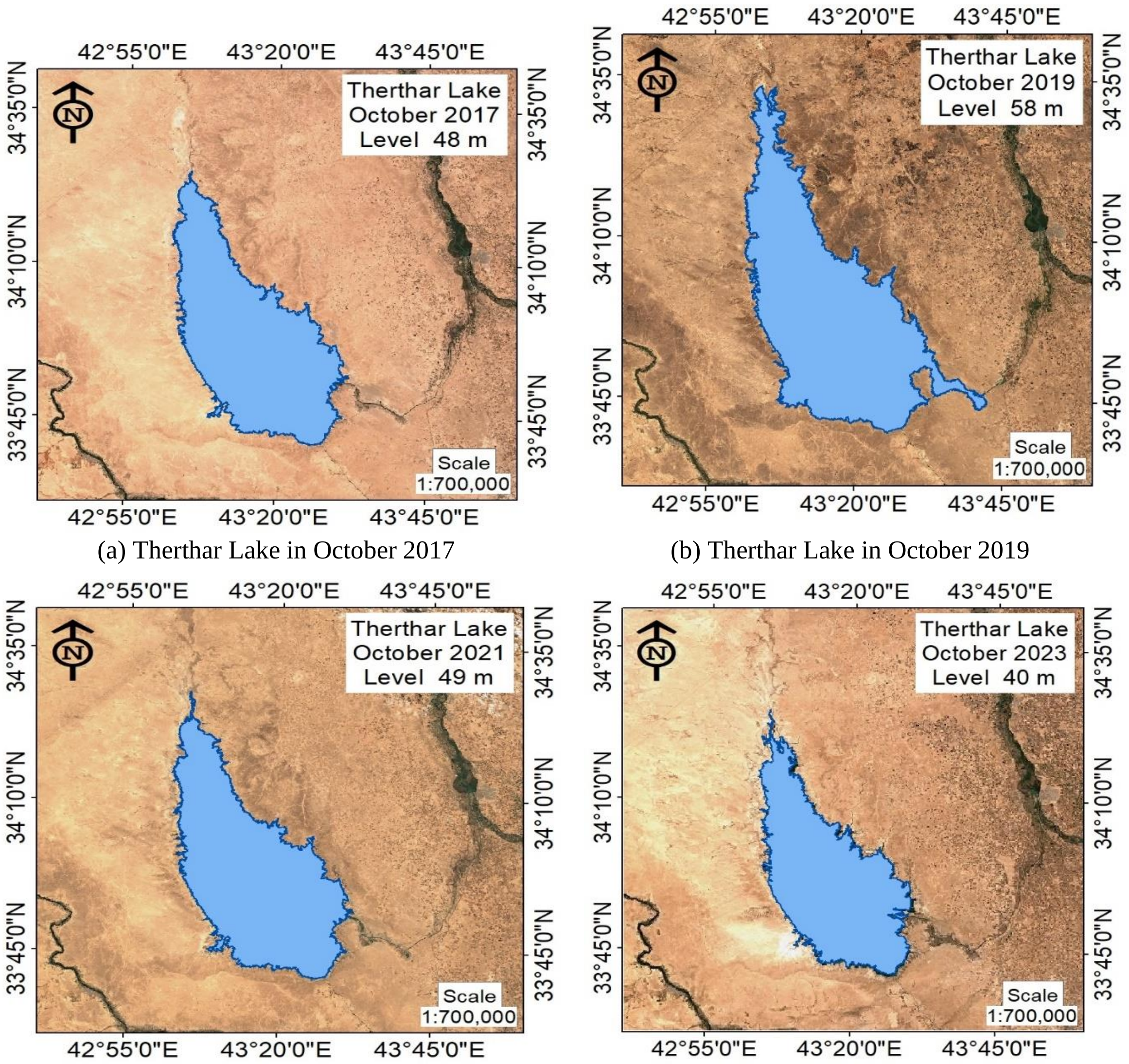
Figure 4. Bathymetric map produced by mosaicking topographic maps

3. Results and discussion

The surface areas and water storage volumes of Therthar depression basin have been obtained based on contours derived from both topographic maps and DEMs. Unlike other relevant studies, this paper presents a novelty in the bathymetric map production and the use of trapezoidal rule for storage volume calculation of lake basins. The variations in surface areas at an interval from 2017 to about the end of 2023 are displayed in Figure 5. The water levels ranged between 40 m to 58 m during this period while the operational level in Therthar depression lake ranges between 40 m to 65 m. When the basin is filled at an elevation 65 m above sea level, the maximum water storage volume is 85.607 bcm. The study proposes expanding the maximum level of Therthar depression according to Therthar arranger design in Samarra that should not exceed 68 m, preferably 67 m above sea level. This is to avoid the reverse effect on Therthar arranger which its gates aperture reaches the maximum 69 m and normal 68 m. The enhancement of the lake storage capacity has an advantage in preventing flood risks opposite a disadvantage of increasing the seepage and soil salinity. Table 3 lists surface areas and water storage volumes at a 5 m contour interval and at a 67 m proposed level. Figure 6 depicts the increment of water storage volumes versus elevations every 5m. The water quantity occurs at an elevation less than 40 m is a dead storage that cannot be utilized in normal situations except when installing pumps.

Annual variations of contour elevations, surface areas and water storage volumes in spring and autumn seasons are listed in Table 4. Figure 7 presents the water storage volume annual changes whereas Figure 8 shows the percentages of these changes from the total storage capacity. The maximum water storage volume occurred in 2019 about 80% from the overall storage capacity. The rainy year 2019 accompanied by the amounts of water received from neighbouring countries, especially Turkey, led to a significant increase in water storage. The satellite image in Figure 5 (b) shows a clear expansion in the lake surface area and shoreline that boosted the water storage compared by other years. In early 2021, the water storage began to decrease substantially due to excessive consumption and factors of evaporation and absorption caused by climatic changes, until reached to a dead storage in 2023. In 2023, only approximately 40 % from the overall storage capacity has remained, that is the lowest water storage since constructing the lake more than half a century ago.

The estimated and actual live storage volumes have been compared. The comparison resulted in RMSE of 0.534 m and R^2 equals to 0.871. This means that 87 % of water storage volume differences are caused by a level change resulting from climatic effects. The rest of the percentage is due to other factors that are not present in the model. Figure 9 shows the water volume differences between estimated and actual live storage versus levels in Therthar depression basin. The simulation of Therthar depression full storage capacity at level 65 m using ArcScene application is represented in Figure 10.



(a) Therthar Lake in October 2017

(b) Therthar Lake in October 2019

(c) Therthar Lake in October 2021

(d) Therthar Lake in October 2023

Figure 5. Therthar depression basin between 2017 and 2023 based on Sentinel images

Table 3: Surface areas and water storage volumes in Therthar depression basin

Level (m)	Surface Area (km^2)	Water Storage Volume (bcm)	Storage Type
0	0	0	Dead Storage
5	534.540	1.336	
10	650.910	4.300	
15	747.862	7.797	
20	859.774	11.816	
25	1011.625	16.494	
30	1167.070	21.941	
35	1323.608	28.168	
40	1477.593	35.171	Live storage
45	1699.768	43.114	
50	1840.410	51.965	
55	2107.915	61.836	
60	2380.118	73.056	
65	2640.472	85.607	
67	2793.644	91.041	Proposed storage
70	2969.115	99.631	

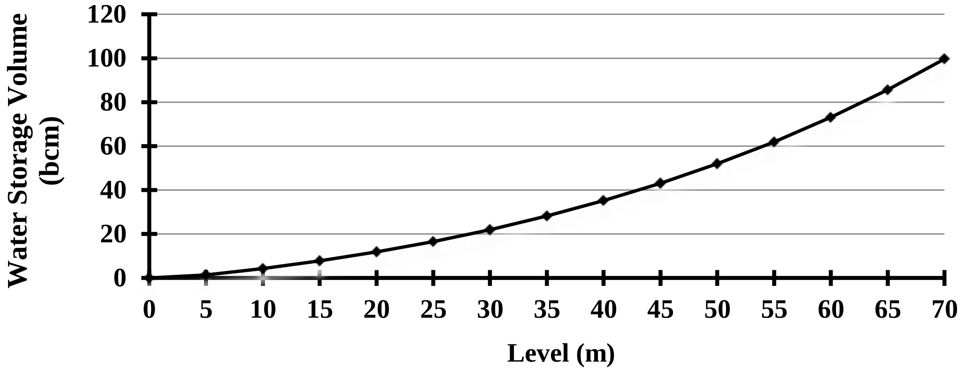


Figure 6. Water storage volumes versus levels in Therthar depression basin

Table 4: Annual changes of contour levels, surface areas and water storage volumes in Therthar depression basin

Date	Contour Level (m)	Surface Area (km^2)	Water Storage Volume (bcm)
May 2017	49	1798.015	50.110
October 2017	48	1756.079	48.298
May 2018	47	1723.164	46.537
October 2018	46	1707.796	44.818
May 2019	58	2271.189	68.404
October 2019	58	2271.189	68.404
May 2020	57	2219.200	66.163
October 2020	56	2165.811	63.973
May 2021	52	1925.468	55.731
October 2021	49	1798.015	50.110
May 2022	45	1699.768	43.114
October 2022	44	1691.735	41.510
May 2023	46	1707.796	44.818
October 2023	40	1477.593	35.171

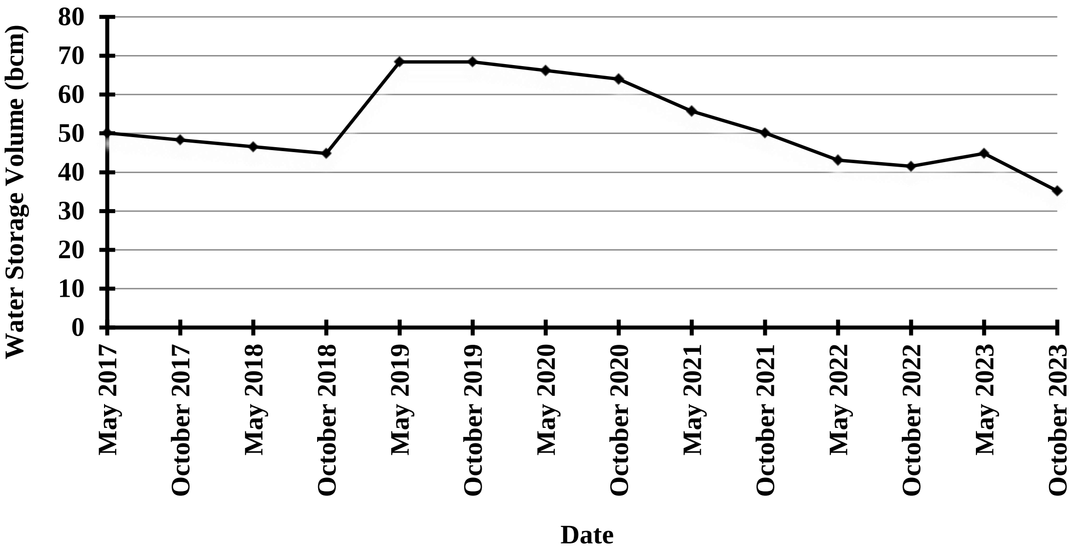


Figure 7. Water storage volume annual changes in Therthar depression basin

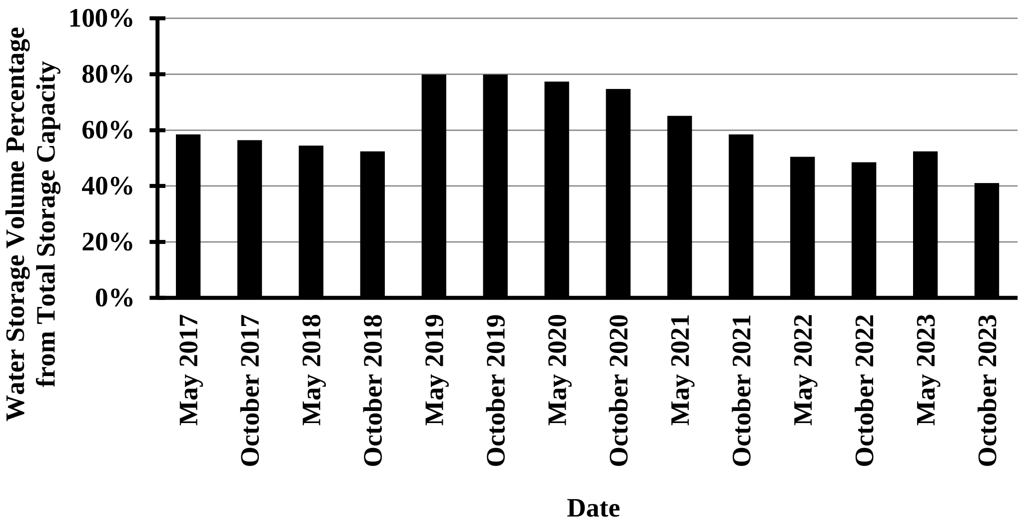


Figure 8. Annual water storage volume percentages from the total storage capacity in Therthar depression basin

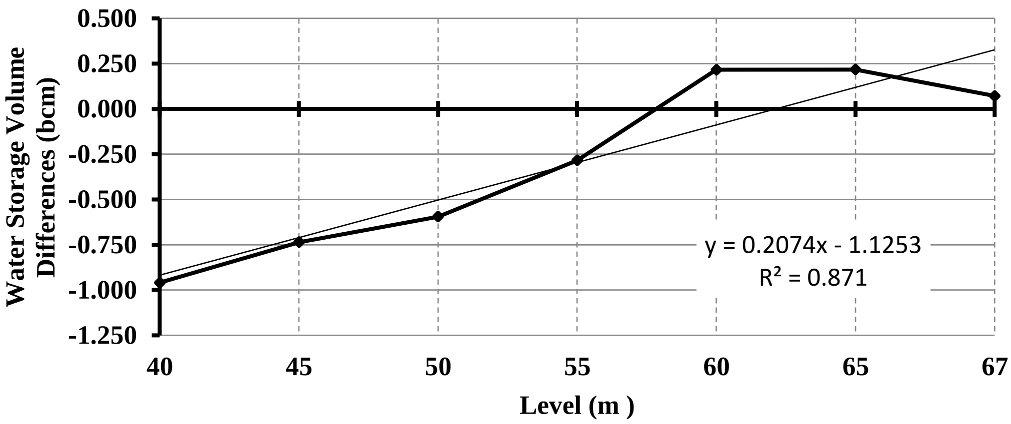


Figure 9. Live storage differences versus levels in Therthar depression basin

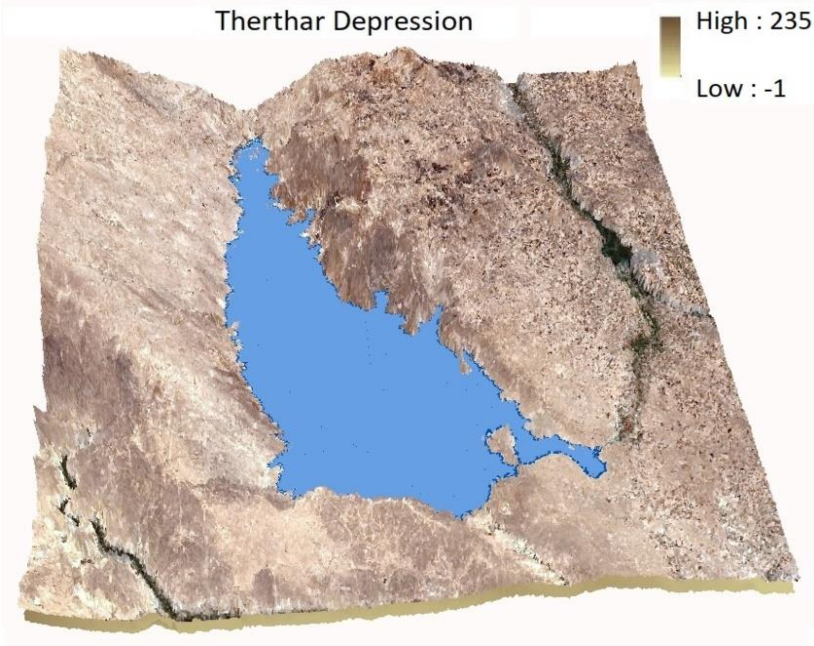


Figure 10. Visualizing Therthar depression basin at 65 m using ArcScene

3.1 Annual water storage and consumption

Water resources planning and management require an estimation of annual water storage and usage. This study offers a new contribution in estimating the excess quantities of water consumption over the water storage in Therthar depression basin as indicated in Table 5. The water consumption exceeded the water storage by 5.292 bcm and 13.127 bcm in May and October months, respectively between 2017 and 2023 years. The percentage of a dead storage is about 40 % from the total storage capacity. The live storage that can be utilized by drainage arrangers is starting from an elevation 40 m. On the other hand, it should be taken into account a portion loss from that live storage volume as a result of annual evaporation and absorption related to the lake surface area as illustrated in Figure 11.

Table 5: Annual water storage and consumption in Therthar depression basin

Year	May			October		
	Water Storage Volume (bcm)	**Storage (bcm)**	**Consumption (bcm)**	**Water Storage Volume (bcm)**	**Storage (bcm)**	**Consumption (bcm)**
2017	50.110			48.298		
2018	46.537		3.573	44.818		3.480
2019	68.404	21.867		68.404	23.586	
2020	66.163		2.241	63.973		4.431
2021	55.731		10.432	50.110		13.863
2022	43.114		12.617	41.510		8.600
2023	44.818	1.704		35.171		6.339
Sum		23.571	28.863		23.586	36.713
Difference	5.292 bcm			13.127 bcm		

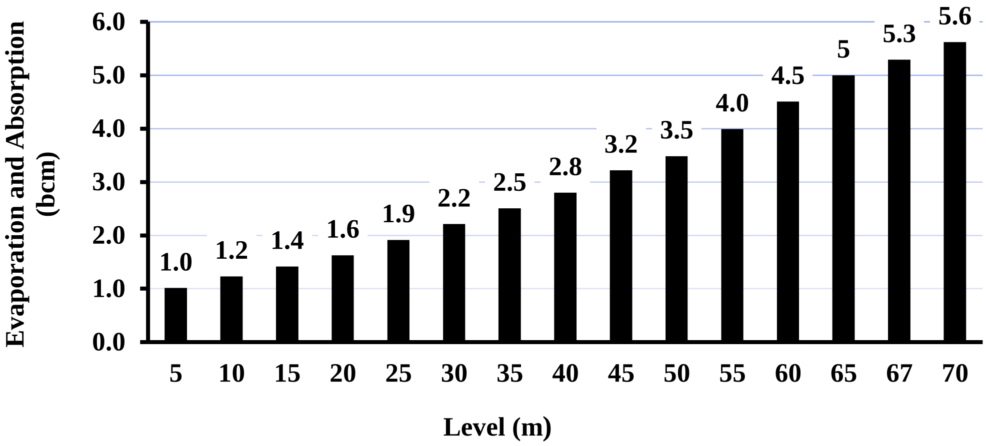


Figure 11. Evaporation and absorption versus levels in Therthar depression basin

4. Conclusions and recommendations

Climatic changes and topographic factors have a significant impact on lakes expanding or shrinking. In 2019, the water storage volume was the most abundant about 80 % from Therthar depression basin overall storage capacity, while in 2021, the water storage volume decreased until reached a dead storage in 2023 to roughly 40 % from the entire storage capacity. Therthar depression basin is strategic water storage. The water consumption exceeded the water storage by 5.292 bcm and 13.127 bcm in May and October months, respectively between 2017 and 2023 years. One of the most challenges facing the lake management is to prevent its future disappearance risk by restricting water consumption rates and issuing strict legislations in line with annual revenues and population increment in urban and agricultural areas. The wide surface area of Therthar depression basin causes large water losses as a result of evaporation increasing. To reduce evaporation amounts, it is preferable to plant perennial trees densely on the lake bank to serve as surface wind buffers, tourism purposes, and residential complexes construction. The comparison between estimated and real live water storage volumes resulted RMSE and R^2 equal to 0.534 m and 0.871, respectively. The water storage volume is highly related with a level change. Open source DEMs have a shortcoming in representing the underwater topography as the entire lake water elevations appear in one level at a satellite image capture moment. In addition, the wide area of Therthar depression and the difficult accessibility from security perspective nowadays make field measurement unattainable. A new approach was adapted in producing a bathymetric map by merging contours derived from both topographic maps and DEMs in ArcGIS environment. This procedure minimizes the time and cost required for data collecting and processing. The storage capacities were estimated using the trapezoidal rule for volumes. The paper recommends improving the design elevation of Therthar depression basin to a level not exceeding 68 m, preferably 67 m above sea level, to avoid the reverse effect on Therthar arranger in Samarra which its gates aperture reaches the maximum 69 m and normal 68 m.

Abbreviations

bcm	billion cubic meters
RMSE	Root Mean Square Error
R^2	coefficient of determination
DEMs	Digital Elevation Models
GIS	Geographic Information System
SRTM	Shuttle Radar Topography Mission
GPS	Global Positioning System
TIN	Triangular Irregular Network
WGS	World Geodetic System
UTM	Universal Transverse Mercator

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