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Effect of Evaporation on the Haditha Reservoir on the Euphrates River in Iraq and Recommendations for Reducing Evaporation Losses

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Abstract

Lakes and reservoirs behind dams are important elements for sustaining ecological balance. They play vital functions at various times and for different purposes, such as supplying water for irrigation, hydropower, and mitigating disastrous environmental effects and impacts, as well as ensuring flood mitigation, insurance during periods of drought, etc. However, these artificial lakes and reservoirs evaporate more rapidly than did the natural surface water flow before the dam was built because dams generally increase the surface area of the body of water. Thus, more of the water surface is exposed to air and direct sunlight, increasing evaporation. This “lost” water is referred to as having been consumed because it is removed from the system. In some cases, this water consumption can be quite substantial. The present trend of global warming speeds up the shrinkage of the water area relative to the land area. This is especially true for lakes and reservoirs, and the environment around them undergoes changes that have degraded the lives of the inhabitants and impacted their economic activities. Many of the world’s lakes and reservoirs are facing the threat of shrinkage. The present study reviews the evidence that demonstrates the high evaporation rates at the Al Haditha Reservoir during the past few decades, with the consequent degradation of its environment that accompanies the changes in the area covered.

Keywords: Dam Lakes and Reservoir, Shrunken Lake, Evaporation, Haditha Reservoir

INTRODUCTION

In hot, dry areas, the loss of water from a dam’s reservoir is striking. Over seven years beginning in 2003, parts of Turkey, Syria, Iraq, and Iran along the Tigris and Euphrates Rivers lost 144 km³ of stored fresh water—about the same as the total amount of water in the Dead Sea—according to data compiled by the GRACE mission and released on Feb. 2014.

A small portion of the water loss was due to soil drying up because of a 2007 drought and to a poor snowpack. More was lost to evaporation from lakes and reservoirs. However, the majority of the water lost, 90 km³ or about 60% was due to reductions in groundwater.

Particularly in arid and semiarid regions, precipitation is both extremely limited and spatially distributed, with the available ground water poor in both quantity and quality. Evaporation from a dam’s reservoir and lagoon constitutes a huge loss of water resources. For example, the annual evaporation losses from behind the Mosul and Haditha dams amounted to more than 2 km^3. The present study estimates the amount of water loss due to evaporation from the Haditha Reservoir (Fig. 1) and considers its effect on water quantity and quality. The need to prevent enormous evaporation losses assumes even greater significance in view of the predictable scarcity of water the country will be facing in the future. Many ideas and techniques have been introduced by water-resource-management specialists to decrease the amount of water lost by evaporation from open-water surfaces.

Loss of surface water from the Haditha Reservoir

Scientists using the twin gravity-measuring satellites that comprise the Gravity Recovery and Climate Experiment (GRACE) have found that a large portion of the Middle East lost fresh-water reserves rapidly during the past decade. The research team observed the Tigris and Euphrates river basins—including parts of Turkey, Syria, Iraq, and Iran—and found that 117 million acre-feet (144 km^3) of fresh water had been lost between 2003 and 2009. That amount is roughly equivalent to the volume of the Dead Sea. About 60% of the loss was attributed to pumping of groundwater from underground reservoirs.

The two natural-color images (Fig. 2) were acquired by the Landsat 5 satellite, and these images show the shrinkage of the Haditha Reservoir in Iraq between September 7, 2006, and September 15, 2009. Both images are shown at the same scale.

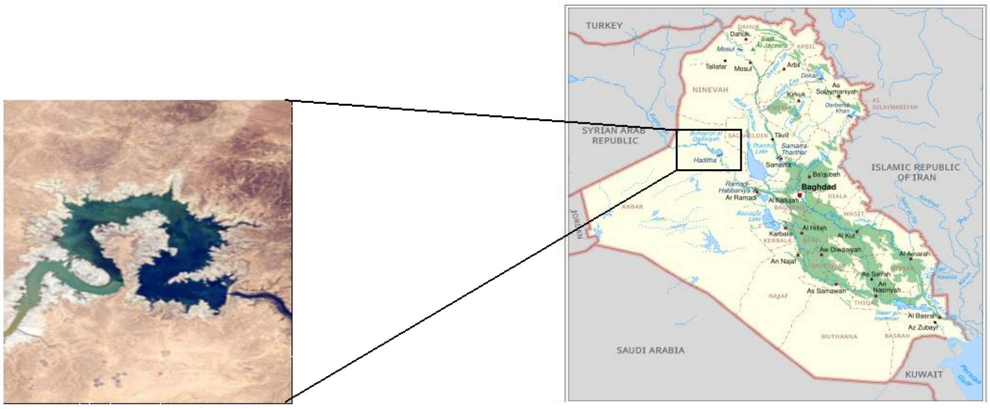
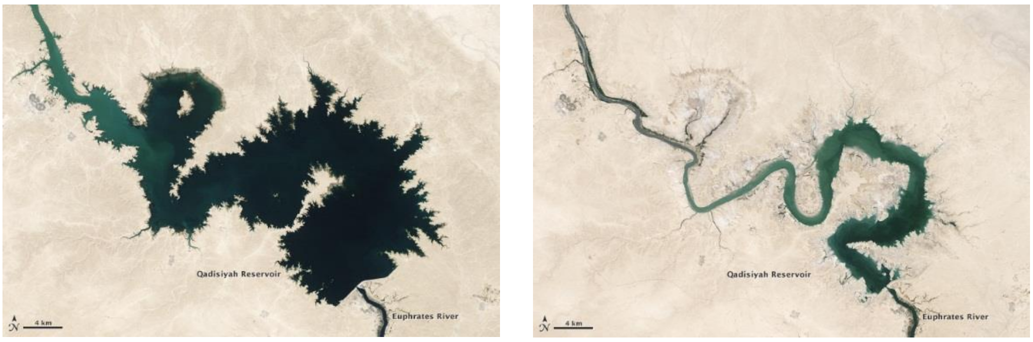


Figure 1. Location of the Haditha Dam and Reservoir



Acquired September 7, 2006 Acquired September 15, 2009

Figure 2. Shrinkage of the Haditha Reservoir

The upper panel in Fig. 3 shows the elevation of the water in the Haditha Reservoir between January 2003 and December 2009. The elevation is a proxy measurement for the total volume of water stored there; labels show the water elevation at the times of the satellite images.

The lower panel in Fig. (3) shows the water storage for the entire study area, as measured by GRACE from January 2003 to December 2009. The gray line depicts the total water storage in the region—groundwater, surface water bodies, and soil moisture—whereas the green line depicts changes in surface water. The difference between those two lines reflects the change in water stored in underground aquifers (ground water). The total water storage shows a seasonal fluctuation, but there is also a pronounced overall downward trend, indicating that groundwater is being pumped and used faster than natural processes can replenish it.

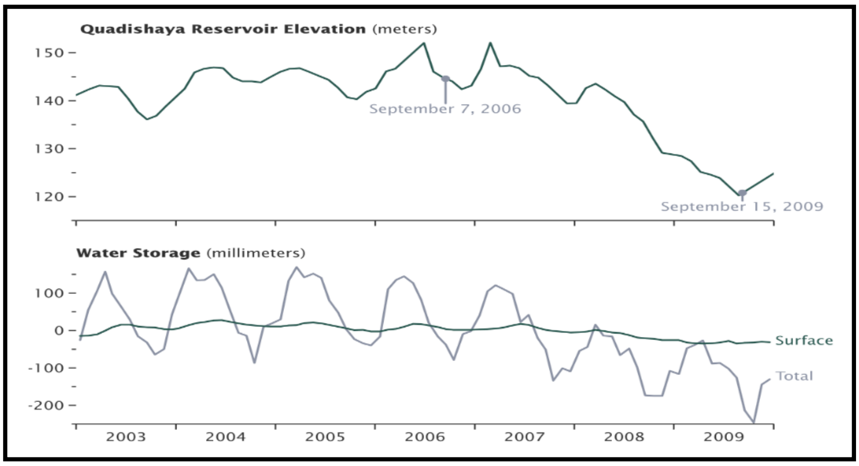


Figure 3. Haditha Reservoir water elevation and water storage

"GRACE data show an alarming rate of decrease in total water storage in the Tigris and Euphrates river basins, which currently have the second fastest rate of groundwater storage loss on Earth, after India," said Jay Famiglietti, principal investigator of the study. "The rate was especially striking after the 2007 drought. Meanwhile, demand for freshwater continues to rise and the region does not coordinate its water management because of different interpretations of international laws."(Famiglietti et al., 2013)

Importance of studying the water balance of lakes and reservoirs

The *Encyclopedia of Lakes and Reservoirs* defines lakes and reservoirs as follows: "Lakes are formed when depressions are filled with water; reservoirs are artificial lakes created behind a dam or between dykes." (Bengtsson et al., 2012). The world has about nine million lakes, and they cover a total surface area of around 1,600,000 km^2. The total water storage in these lakes is about 230,000 km^3 (Bengtsson et al., 2012). Many large dams are still being planned or are under construction, so the number of reservoirs is increasing.

The general water-balance components of lakes and reservoirs

In general, the water-balance equation for a lake or reservoir can be written as (Ferguson and Znamensky, 1981; Sokolov and Chapman, 1974)

$$dVlake/dt = Rland + \mathbf{A}lake\ (Plake - Elake) + Gi - Go - Olake + \varepsilon \quad (2.1)$$

whereVlake is the water volume stored in the lake (or reservoir),dVlake/dt is the time rate of change in that water volume, Rland is the rate of surface inflow into the lake from the surrounding land-based river basins, Alake is the surface area of the lake, which is a function of water level, Plake is the precipitation over the surface of the lake, Elake is the rate of evaporation from the lake, Gi and Goare, respectively, the rates of groundwater inflow to and outflow from the lake, Olake is the surface outflow from the lake, and ε represents the accumulated errors from all components in Eq. (2.1), together with other factors, such as abstraction and human water use. These factors usually cannot be accounted for directly and have been assumed to be zero in many water-balance studies (Sene, 2000). The term R_{land} links a lake or reservoir with the water yield from the surrounding catchments. The simple water-balance equation for the catchments feeding a lake can be written as

$$dSland/dt = Pland - ETland - Rland, \quad (2.2)$$

where dS_{land}/dt is the time rate of change in total water storage on land, S_{land}; the quantity P_{land} is the precipitation over the river basin; and ET_{land} is the actual evapotranspiration over the river basin. Fig. (4) shows the general water-balance components for a lake or reservoir and its catchment areas. Their relative importance and the need to consider each individual component in the water-balance equation can vary depending on the type and dimensions of the lake. For example, some lakes (e.g., the Caspian Sea, Lake Chad, and the Dead Sea) are terminal lakes with no outflow, whereas some kettle lakes are parts of the groundwater system, having only groundwater inflow and outflow (Bengtsson et al., 2012). For a lake with a relatively small drainage basin, precipitation and evaporation over the lake surface are usually the dominant water-balance components. To close the water-balance equation for a lake or reservoir, all components must be measured or estimated independently (Sokolov and Chapman, 1974). A common usage of the water-balance equation is to estimate the residual unknown component. The accuracy of the estimated component depends on the accuracy of each known component and includes the accumulated errors from all of the components. It is thus necessary to improve the quantification of each water-balance component independently.

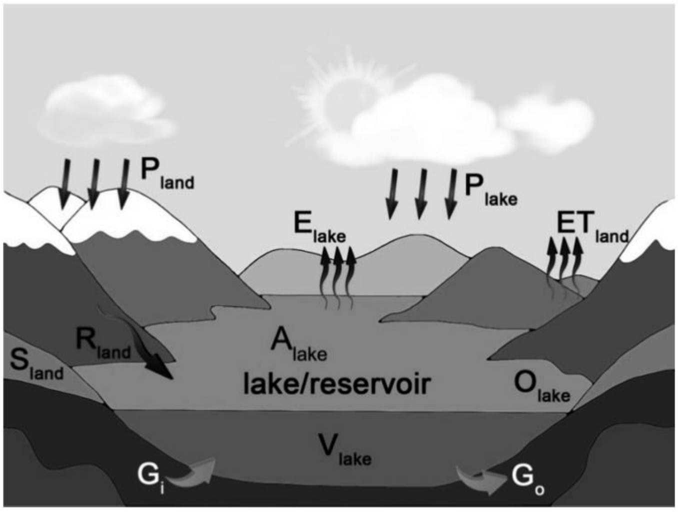


Figure 4. The general water-balance components for a lake or reservoir and its surrounding catchments

Surface inflow into lakes and reservoirs

The inflow into lakes or reservoirs can be determined by *insitu* measurements of runoff from the contributing catchments. However, in most cases, upstream sub-basins are only partially gauged.

For example, approximately 50% of the catchments contributing to the inflow into Lake Victoria (Kizza et al., 2011) and Lake Tana (Wale et al., 2009) are ungauged, which makes it difficult to estimate the total water yield. Reasonable estimates of inflow involve basin-scale rainfall-runoff modeling and studies of runoff prediction in ungauged basins. The details of the methods for runoff prediction in ungauged basins (PUB) can be found in a recent book by Bloschl et al. (2013). Hrachowitz et al. (2013) provided a comprehensive review of the research progress and challenges in PUB. Winsemius et al. (2008; 2009) discussed specifically the calibration of hydrological models for ungauged basins. The consequence of incomplete data on inflows is that estimates of lake evaporation and lake interactions with groundwater also become incomplete. Lake interactions with groundwater are very difficult to assess and can only be obtained by accounting for all other flows with high accuracy. Thus, the reality is that the water balance for a lake or reservoir is usually incomplete.

Precipitation over the water surfaces of lakes and reservoirs

Precipitation falling directly onto the water surface can be measured by installing rain gauges over lakes and reservoirs. For large lakes or reservoirs, more than one gauge is needed to determine the spatial-average precipitation with reasonable accuracy. However, such measurements are often lacking. For most lakes and reservoirs, there are no gauging stations at all installed over the surface. As a result, it is still common practice to use precipitation measured on nearby land or the shoreline to determine lake precipitation. For this purpose, directly measured precipitation data from either one land-based gauge station or interpolated precipitation from several available nearby stations is used (e.g., Kebede et al., 2006; Rientjes et al., 2011). However, previous studies showed that, for large lakes, nocturnal lake-breeze effects can markedly enhance rainfall over the center of the lake, and hence, the nearby land-based rainfall may considerably underestimate the actual lake rainfall (Kizza et al., 2012; Yin and Nicholson, 2002).

Water volume of lakes and reservoirs

The volume of water stored in a lake or reservoir is the water directly available for downstream users. Information on changes or variations in water volume is needed for the water-balance equation [Eq. (2.1)]. The volume of water stored in a lake or reservoir cannot be measured directly. The determination of water volume requires information about the water level and water surface area. Traditionally, the water volume in a lake or reservoir is estimated based on *insitu* water levels and bathymetry maps. Water levels can be measured with *insitu* gauging stations installed near river mouths, bridges, weirs, or sluices. Bathymetry maps can be obtained from hydrologic surveys, which use sonar sensors on ship transects to measure the underwater topography. On the basis of a bathymetry map, one can derive functional area-level and volume-level relationships and can then compute the water volume and surface area for a given water level. Bathymetry maps are often non-existent or difficult to obtain for a given lake or reservoir. In addition, the number of *insitu* gauging stations around the globe has decreased in recent years (Alsdorf et al., 2007; Calmant et al., 2008; Cretaux and Birkett, 2006), which makes *insitu* water levels more scarce.

Evaporation from lakes and reservoirs

Evaporation is generally considered to be the largest water loss for many lakes and reservoirs (Kizza et al., 2012). It can be determined using the Bowen ratio or eddy-covariance techniques (Assouline and Mahrer, 1993; Blanken et al., 2000; Stannard and Rosenberry, 1991). Eddy-covariance measurements are operationally difficult, however, and they have only been conducted for a limited number of lakes and over short periods. Long-term measurements of evaporation from lakes and reservoirs are lacking almost everywhere. Many methods have been proposed for estimating evaporation from lakes and reservoirs, including the water-balance method, mass-transfer method, energy-balance method, combination method (Lowe et al., 2009), and surface-renewal analysis (Mengistu and Savage, 2010). Comprehensive reviews of methods for estimating evaporation can be found in Brutsaert (1982) and Finch and Calver (2008). **Among many methods, the energy-balance method is generally considered to be the most accurate for estimating evaporation over timescales of a week or longer (Rosenberry et al., 2007; Winter, 1981).However, data requirements for the energy-balance method are also the most intense**. Energy-balance combination models (e.g., due to Penman, Priestley–Taylor, or De Bruin–Keijman) have been shown to generate lake-evaporation estimates that compare most closely with the energy-balance method (Rosenberry et al., 2007; Elsawwaf et al., 2010). Depending on the complexity of a particular combination method, the required data include three or more of the following variables: net radiation, heat-storage changes, air temperature, relative humidity, and wind speed.

In general, the estimation of evaporation from lakes and reservoirs suffers from two major difficulties: (i) the meteorological variables required by different computational methods should be measured over water surfaces, but this requirement is rarely met. (ii) The heat-storage effect due to seasonal heat inertia should also be considered. This effect is caused by the penetration of radiation into the water body, coupled with the large heat-storage capacity of water. The result is that part of the heat energy is stored in the water body during the spring and summer periods, and the stored heat is released during the autumn and winter periods (Finch and Hall, 2001). As a result, evaporation from a lake or reservoir is not necessarily in phase with the net radiation. To account for the heat-storage effect, heat-storage changes can be calculated based on the water-temperature profile (Gianniou and Antonopoulos, 2007). However, such data are rarely available for the vast majority of lakes and reservoirs in the world (Kirillin et al., 2011). The Distributed Temperature Sensing (DTS) approach shows great potential for the measurement of lake water-temperature profiles and air-water interfacial temperatures in a lake (Selker et al., 2006; van de Giesen et al., 2012; van Emmerik et al., 2013).

New measurement techniques (e.g., DTS) with lower costs are needed to make measurements of the necessary variables—over the water surface and within a lake—both practical and operational in the future. Due to the general lack of data regarding these two quantities, data from nearby land-based stations are often used to estimate evaporation from a lake or reservoir, and the heat-storage-change term is ignored in many studies. The heat-storage change is generally close to zero on an annual time scale, but it can be significant on monthly time scales (Bengtsson et al., 2012), and the neglect of this term can result in significant errors in estimates of lake evaporation on monthly or shorter timescales. Therefore, in order to improve evaporation modeling, it is necessary to develop methods to quantify the heat-storage-change term based on more readily available data.

Groundwater flows for lakes and reservoirs

Groundwater inflow into and outflow from lakes and reservoirs are probably the most difficult water-balance components to evaluate owing to the requirements for laborious and costly measurements (Ferguson and Znamensky, 1981). Crowe (1993) concluded that three methods can be used to quantify groundwater flows into or out of a lake or reservoir; they include a field-oriented method, a numerical simulation, and a water-balance method. The water-balance method is the one most commonly used; it estimates the groundwater component as the residual in the water balance of a lake or reservoir. As a result, this method requires other water-balance components to be known, and it can only estimate the net groundwater flow (the difference between groundwater inflow and outflow) rather than individual inflow and outflow components (Crowe, 1993; Kirillin et al., 2013). Coupled with the water-balance method, environmental-isotope techniques have been used to quantify separately the groundwater inflow and outflow for lakes (Gurrieri and Furniss, 2004; Kluge et al., 2012; Nachiappan et al., 2002; Turner et al., 1984). These techniques require laborious field-sampling measurements, which are only conducted in dedicated scientific studies. Crowe and Schwartz (1985) pointed out that quantifying groundwater inflow and outflow from lakes is cumbersome, and it is more convenient to assume groundwater flows to be negligible. For example, groundwater inflow and outflow were assumed negligible for Lake Victoria (Piper et al., 1986), Lake Tana (Rientjes et al., 2011), Lake Malawi (Kumambala and Ervine, 2010), Lake Turkana (Velpuri et al., 2012), Lake Alemaya (Setegn et al., 2011a), and Lake Edward (Russell and Johnson, 2006). However, hydro-geologists argue that it is physically impossible for groundwater flows to be negligible.

Surface outflows from lakes and reservoirs

The surface outflow from a lake or reservoir is the water released downstream to multiple sectors. For upstream water-level control, the outflow can be estimated using the water level h and a predefined level-outflow functional relationship $Q(h)$ or rating curve (Nicholson et al., 2000; Piper et al., 1986). The $Q(h)$ relationship incorporates site-specific hydraulic structures, such as gates, weirs, and turbines (e.g., Bos, 1989). Historical *insitu* measurements of Q and h are needed to reconstruct the rating curve, and the $Q(h)$ relationship is usually not available for lakes and reservoirs. In addition, the $Q(h)$ relationship may change over time for the same water body owing to hydraulic modifications or clogging features. In the absence of a locally calibrated $Q(h)$ relationship, the universal method for estimating outflow is to quantify independently all of the other water-balance components for a lake or reservoir and then to compute the outflow as the residual term in the water-balance equation.

CASE STUDY: The Haditha Dam Reservoir

Located on the Euphrates River7 km upstream from the town of Haditha and about 120 km from the Syrian border, the Haditha Dam is an earth-fill dam, which has created Lake Haditha (the Haditha Reservoir). The purpose of the dam is to generate hydroelectricity, regulate the flow of the Euphrates, and provide water for irrigation. It generates 660 MW and is the second largest hydroelectric contributor to the power system in Iraq behind the Mosul Dam. The Haditha Dam is just over 9 km long and 57m high. The width of the crest is 20 m, and its level is 154 m. At the operational level of 147 m, the area of the reservoir is 500 km^2, and the storage volume at that level is 8.25 billion cubic meters (BCM). The top level in full flood is 150.2 m, and at that level, the area of the reservoir is 567 km^2, and the storage volume is 9.8 BCM.

Haditha Dam Reservoir has resulted from the storage of water since 1986. It is located in the western part of the Euphrates River, between longitude (41°55′–42°27′) east and latitude (34°13′–34°40′) north. The reservoir extends for 100 km upstream of the Abushabor “site of the dam” in the south to Rawa city in the northwest. The minimum width of the reservoir is 2 km, and the maximum width is 11 km, with an average depth of 17 m. The surface area of the reservoir is 500 km^2. The live and dead storage capacities of the reservoir are 8.28(BCM) the level of 147 m and 0.23(BCM) at the level of 112 m, respectively. The surface storage area is 500 km^2 at the level of 147 m. The area is characterized by its desert climatic conditions (i.e., evaporation rates exceed the precipitation ;Al-Hadithi 1994).The bed of the reservoir is covered with recent sediments and consists of silt, sand, and gypsum deposits.

Objective of the study

The main objective of this research is to estimate the evaporation losses from the Haditha Reservoir during the time period from 2006 to 2009 when the reservoir shrank considerably and to introduce a new technique for decreasing the evaporation losses.

Location of the study area

The study area lies in the western part of Iraq, within Al-Anbar Governorate, and it covers about 500 km^2. It is located at the following coordinates: 41°55′–42°27′E, 34°13′–34°40′ N.

Climate

The region around the reservoir has a hot, desert climate, with an average annual precipitation of 127 mm (the amount ranges between 45 and 200 mm). The wet period extends between November and April, whereas the dry period extends from May to October.

Geological setting

The reservoir site is located within the marginal area of the northern slope of the Arabian–African platform, where it borders the Alpine folded zone. Previous investigations have revealed complex geological conditions at the site. There are faulted strata of limestone and dolomites, with occasional karst and numerous heterogeneous varieties.

DEFINITION OF EVAPORATION

Evaporation is the process by which a liquid changes into vapor form. Water molecules are in constant motion, and some have enough energy to break through the water surface and escape into the air as vapor. Evaporation, in general, helps in regulating global water balance through the hydrological cycle, and it contributes to massive losses from water bodies. Control of evaporation from land-based water bodies has thus remained one of the main planks of water-conservation strategies. It assumes greater significance in arid regions, where water scarcities are already a common problem.

Dalton's law of evaporation

In the atmosphere, the rate of evaporation depends upon the difference between the saturation vapor pressure and the actual vapor pressure. Therefore, John Dalton suggested the formula

$$E = C(e_w - e_a), \qquad (4.1)$$

Where E is the evaporation rate, C is a constant, $e_w$is the saturated vapor pressure at the given water temperature, and $e_a$is the actual vapor pressure in the air.

Factors influencing evaporation

A number of factors affect the evaporation rate from an open-water surface. The major ones are the following:

The water surface area

Evaporation is a surface phenomenon, and the quantity lost through evaporation from stored water therefore depends directly on the extent of the surface exposed to the atmosphere.

Temperature

The temperatures of the water and the air above it affect the rate of evaporation. The rate of emission of molecules from liquid water is a function of temperature. The higher the temperature, the greater is the rate of evaporation.

Vapor pressure difference

1. The rate at which molecules leave the surface depends on the vapor pressure of the liquid. Similarly, the rate at which molecules enter the water body depends on the vapor pressure of the air. The rate of evaporation therefore depends on the difference between the saturation vapor-pressure values at the water temperature and at the dew point of the air. The greater the difference, the more the evaporation.

Wind effect

The greater the movement of air above the water, the greater is the loss of water vapor. Experimental studies on the relationship between wind speed and evaporation show a direct relationship up to a certain value of wind velocity, beyond which the relationship may not hold. Factors like surface roughness (e.g., waves) and the dimensions of the water body are reported to have important roles to play.

Atmospheric pressure

Atmospheric pressure is closely related to other factors affecting evaporation. It is therefore difficult to assess its effect separately. The number of air molecules per unit volume increases with pressure. Consequently with high pressure, there is a greater chance that vapor molecules escaping from the water surface will collide with an air molecule and rebound into the liquid. Hence, evaporation is likely to decrease with increasing pressure.

Quality of water

The salt content of water affects the rate of evaporation. Experimental studies show that the rate of evaporation decreases with increasing salt content of the water. In the case of sea water, the evaporation rate is 2% to 3% less than that for fresh water, with other conditions being the same.

Heat storage in water bodies

Deep water bodies have more heat storage than shallow ones.

ESTIMATION OF EVAPORATION

There are several methods for estimating the rate of evaporation from open-water surfaces. They include the following: evaporimeters, empirical evaporation equations, and analytical methods for estimating evaporation rates.

Evaporimeters

The various types of evaporimeters include the Class A Evaporation Pan, the Colorado Sunken Pan, and the US Geological Survey Floating Pan. However, evaporation pans are not exact models of large reservoirs. In particular, they have the following principal weaknesses:

1. They differ in the heat-storage capacity and in the amount of heat transfer from the sides and bottom of the pan. (Both the sunken pan and the floating pan aim to reduce this deficiency.) As a result, the evaporation from a pan depends to a certain extent on

its size.

2. The height of the rim in an evaporation pan affects the wind action over the surface.
3. The heat-transfer characteristics of the pan material are different from that of the reservoir.

Empirical evaporation equations

A number of empirical equations are available for the estimation of evaporation. Some commonly used expressions include the following:

1. Meyer's Formula: E=$K_m(e_w - e_a)\left(1 + \frac{U_a}{16}\right)$. (5.1)

Here, E is evaporation (mm), e_w is the saturated vapor pressure (mmHg) at the water-surface temperature,$e_a$is the actual vapor pressure in the air (mmHg), and U_a is the wind velocity at a height of 9 m above ground level. The coefficientK_m is a parameter accounting for other factors, such as the size of the water body; it is generally taken to be 0.36 for large lakes and 0.50 for small water bodies.

2. Fitzgerald's Formula: E=$(0.4 + 1.24u_0)(e_w - e_a)$. (5.2)

Here,u_0 is the wind velocity at the land surface.

3. Rower's Formula: E= $0.771(1.465 - 0.000732p_a)(0.44 + 0.0733u_0)(e_w - e_a)$ (5.3)

In this equation, p_a is the mean barometric pressure (mmHg), and u_0 is the mean wind velocity (in km/h) at ground level (taken as the wind velocity at a height of 0.6 m above the ground).

4. Wind velocity:

In the lower part of the atmosphere, up to a height of about 500 m above ground level, the wind velocity follows a one-seventh power law. This law is the simplest way to estimate the wind speed at a wind-generator hub elevation from measurements at a reference level. In general, the power law expression is given as

$$\frac{u_2}{u_1} = \left(\frac{h_2}{h_1}\right)^p \quad (5.4)$$

where$u_1 and u_2$are the mean wind velocities at, respectively, the measurement height h_1 and the height h_2 at which the wind speed is predicted, and $p = 1/7$is the power law exponent.

Analytical methods for estimating evaporation

The analytical methods available for estimating the amount of evaporation are the following: the water-budget, energy-budget, mass-transfer, Penman, Priestley–Taylor, and De Bruin methods. It is worth noting that the instrumentation required for the energy-budget and mass-transfer methods is expensive, and for this reason, the water-budget method is more commonly used.

Water-budget method

This is the simplest method for determining the amount of evaporation from ponded water such as lakes, but it seldom produces reliable results. The water-budget equation can be written as

Δ storage= Input − Output or $\Delta S=(I+P)-(O+E+GW)$. (5.5)

This can be rewritten in the equivalent form

$$E = -\Delta S + I + P - O - GW \quad , \quad (5.6)$$

where I is the inflow (cm), P is precipitation (cm), O is the outflow (cm), E is the amount of evaporation (cm), and GW is the groundwater seepage (cm). The accuracy of this method is limited by the estimate of groundwater seepage and the estimate of precipitation.

Energy-transfer method

In this method, the energy available for evaporation is determined by considering the incoming, outgoing, and stored energy in the water body at a given time. This method is an application of the equation of conservation of energy. The energy-budget equation can be written as

$$Qn = Qh + Qe + Qg + Qs + Qi, \quad (5.7)$$

Where *Qn* is the net heat energy received by the water surface, *Qh* is the sensible heat transfer, *Qe*is the energy lost to evaporation, *Qg*is the heat flux into the ground, *Qs*is the heat stored in the water body, and *Qi*is the advected energy. In order to compute *Qh,* we use Bowen's ratio β is used, which is defined as follows:

$$\beta = \frac{Qh}{Qe} = 6.1 \times 10^4 \rho_a \frac{(T_w - T_a)}{(e_w - e_a)} \quad (5.8)$$

Here, ρ_a is the atmospheric pressure (mmHg), e_w is the saturated pressure (mmHg), e_a is the actual vapor pressure (mmHg), T_w is the temperature of the water surface (°C), and T_a is the temperature of the air (°C).The limitation of this method is that it requires extensive instrumentations.

Mass-transfer method

This method is primarily based on the concept of turbulent transfer of water vapor from the evaporating surface into the atmosphere. Here, evaporation is driven by the vapor-pressure gradient and the wind speed. For this method, the amount of evaporation is given by

$$E = (a + bu)(e_{s-}e_a) \qquad (5.9)$$

Here, u is the wind speed at some level above the surface, and$a$ and$b$ are empirical constants.

Thornthwaite and Holzman (1939) provided the following equation to compute the amount of water vapor transferred to the atmosphere from a lake surface:

$$E = \frac{0.000119(e_1 - e_2)(u_2 - u_1)}{p \times \left[ln\left(\frac{h_2}{h_1}\right)\right]^2} \qquad (5.10)$$

Here, u_1 and u_2 are wind velocities (m/s) at heights $h_1$and h_2, respectively, e_1 and e_2 are the corresponding vapor pressures (in Pa), and p is the ambient air pressure.

Penman Method

The Penman method is perhaps the most popular in evaporation studies. It belongs to the category of combination methods, which are so-named because they combine aspects of the energy-budget and mass-transfer methods. The Penman method is expressed by the following equation:

$$E = \frac{\Delta}{\Delta + \gamma} \frac{(Q_m - Q_t)}{\rho_w L_v} + \frac{\gamma}{\Delta + \gamma} f(u)(e_{s\alpha} - e_d) \qquad (5.11)$$

where Δ is the slope of the curve of saturation vapor pressure versus air temperature (mbar°C⁻¹), $e_{s\alpha}$is
the saturation vapor pressure at ambient air temperature (mbar), and Q_m is the net radiation(cal cm^{-2} day^{-1}):

$$Q_m = Q_s - Q_{sr} + Q_a - Q_{ar} - Q_{br} \qquad (5.12)$$

The energy terms *Qs* and *Qa* are estimated from meteorological data, *Qsr* and *Qar* are fixed portions of *Qs* and *Qa* and *Qb*r is estimated from the lake's surface temperature with the use of the Stefan Boltzmann law. The Penman formula consists of two terms, an energy term and an aerodynamic term, which take into account both the energy consumed and the contribution of the wind speed and the vapor-pressure deficit to the evaporation process. The wind function originally proposed by Penman is$f(u) = 0.26(1+0.536u^2)$. Later, he modified this function to $f(u) = 0.26(0.5+0.536u^2)$. The latter formula is more suitable for calculating evaporation from large open-water surfaces.

Priestley–Taylor Method

The Priestley–Taylor method is a modification and simplification of the Penman formula. Priestley and Taylor (1972) estimate evaporation as a function solely of the energy term in the Penman equation, as they argue that—over a suitable averaging period—the aerodynamic term can be approximated as a fixed fraction of the total evaporation. The Priestley–Taylor equation has the form

$$E = \alpha \frac{\Delta}{\Delta + \gamma} \frac{(Q_m - Q_t)}{\rho_w L_v} \qquad (5.13)$$

where α is an empirically derived parameter with an average value α = 1.26. This is equivalent to assuming that the aerodynamic term contributes 21% of the total evaporation. In applying the Priestley–Taylor method, there is no need for wind-speed data or the wind function *f(u).*

De Bruin Method

In contrast to the Priestley–Taylor method, De Bruin used the Penman formula and the Priestley–Taylor parameter α and developed the following equation to estimate evaporation solely as a function of the aerodynamic term in the Penman equation:

$$E = \frac{\alpha}{\alpha - 1} \frac{\gamma}{\Delta + \gamma} \frac{f(u)(e_{s\alpha} - e_d)}{\rho_w L_v} \qquad (5.14)$$

To apply the De Bruin method, there is no need for radiation data or for the determination of the change in the thermal content of the reservoir.

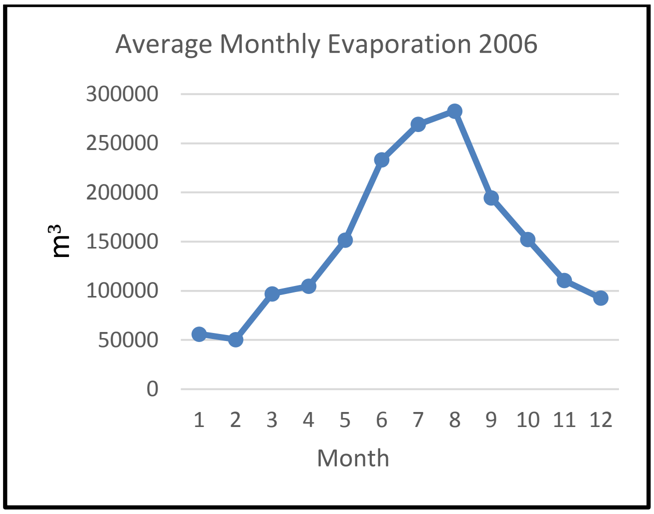
Estimation of evaporation at the Haditha Reservoir over the time period 2006–2009

To calculate the evaporation of the Haditha Reservoir, the time period from 2006 to 2009 was considered, when the reservoir experienced considerable shrinkage and the water level was at its lowest. The average monthly evaporation and the volume of water evaporated from the reservoir were calculated using the available data (Sadeq Oleiwi Sulaiman, 2017), Meyer's formula (Eq. 5.1), and the power law (Eq. 5.4) that gives the wind speed as a function of height.

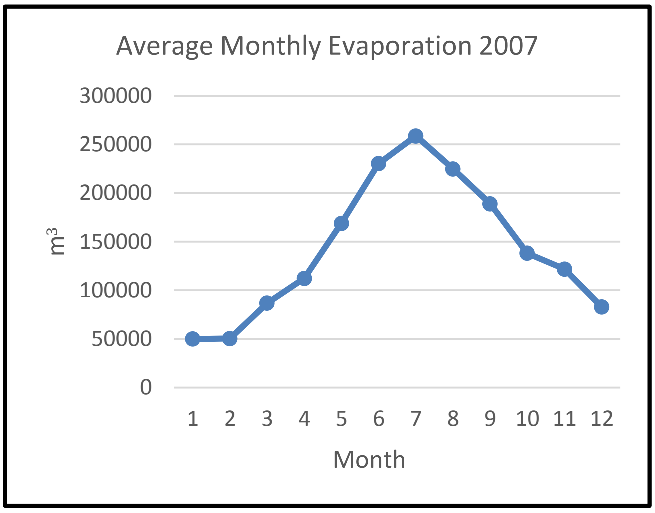
RESULTS AND DISCUSSION

The input meteorological data that has been used to estimate the amount of evaporation from the Haditha Reservoir are the daily values of water-surface temperature, relative humidity, and wind speed provided by the meteorological stations of Haditha and Ana (Sadeq Oleiwi Sulaiman, 2017). The calculations done at the start of the stated time period and continued in daily time steps. Note that faulty meteorological data or the fact that they come from different meteorological stations can sometimes result in fluctuations with the wrong sign. The judgment concerning which of the methods is the most appropriate to use in estimating the amount of evaporation from the Haditha Reservoir depended on exact determinations of evaporation using valid methods. Owing to the sporadic nature of the available meteorological data, not all methods can be used in all cases, and the suitable method has been only selected to use with the existing data to calculate the evaporation.

The mean monthly and average yearly evaporation rates estimated using Meyer's method and the power law (5.4) is shown in Figs. (5 to 9).



(Figure 5)



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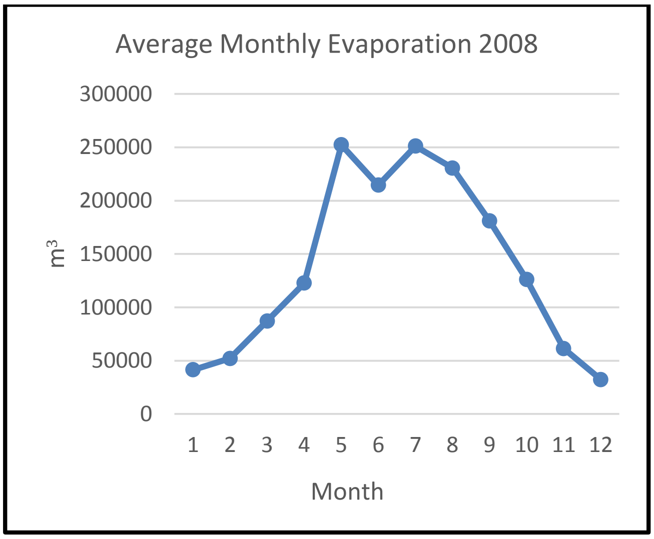

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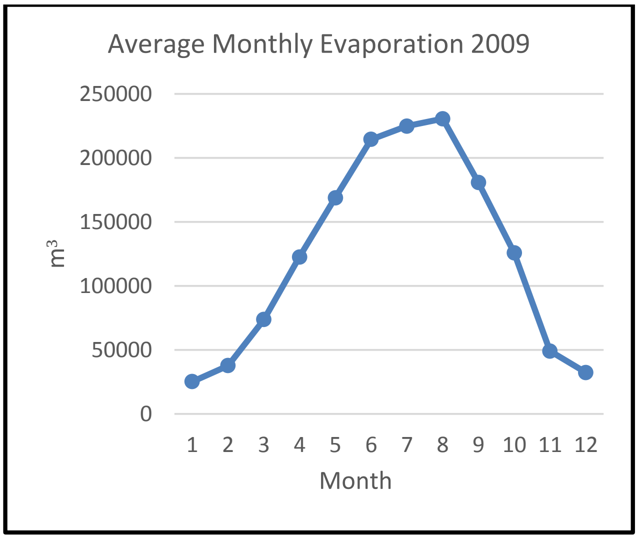

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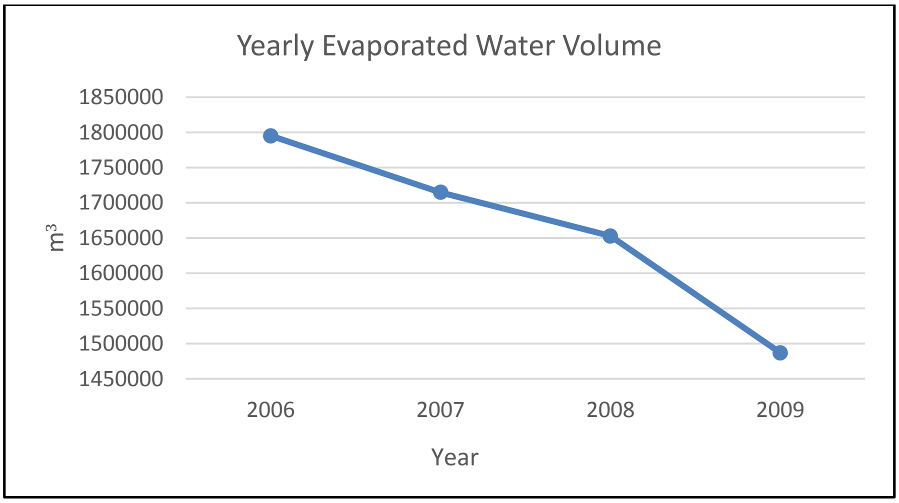

(Figure 9)

CONCLUSION

The availability of climatic data is a main consideration in selecting a method for estimating the evaporation from a large body of water. The energy-budget, Penman, and Priestley–Taylor methods are data-intensive as they require measurements of many meteorological variables. The mass-transfer and De Bruin methods are less data-demanding. In the absence of adequate meteorological data, Meyer's method and the wind-speed *vs.* height power law can be used with sufficient accuracy. With regard to the new technique to decrease evaporation losses from open water surface, it has been shown by the studies that the new technique is based on the concept that the evaporation can be reduced from open water surface using floating cover sheets.

RECOMMENDATIONS FOR REDUCING EVAPORATION LOSSES

Numerous ideas and techniques have been introduced by water-resources-management specialists for decreasing the amount of water lost by evaporation from open-water surfaces. The techniques have been suggested for decreasing evaporation losses from more general open-water surfaces, including the use of floating sheets or monomolecular films, changing the water color so that it absorbs less solar radiation, the use of wind barriers, shading the water surface, or the use of floating covers. The considerable methods and techniques introduced by water resources management specialists to decrease the amount of water lost by evaporation from open water surfaces can be summarized as follows:

Methods to Decrease Evaporation Losses from Open Water Surface

- Changing of the surface area of the lake
- Changing of the water levels upstream the lake.
- Cultivating special Crops on the lake surface.
- Closure of secondary channels.

Techniques to Decrease Evaporation Losses from Open Water Surface

A number of approaches have either been applied or considered by Engineers and Scientists in their attempt to reduce evaporation losses from surface of water bodies. Since the basic meteorological factors affecting evaporation cannot be controlled under normal conditions, efforts have so far been restricted to managing the neither suppression nor inhibition of evaporation from water surfaces by physical or chemical measures. The methods generally used or being tried are listed below:

- Use of floating sheets.
- Use of monomolecular films.
- Changing the water color.
- Use of wind barriers.
- Shading the water surface.
- Use of floating covers.

The Proposed New Techniques

The previous studies which dealt with the evaporation reduction from open water surfaces have had some weaknesses. For example, applying the technique in which all the water surface is covered is not practically acceptable as the complete coverage of the surface prevents the exchange between air and water, a matter which affects the oxygen demand needed by the aquatic ecology. Another shortcoming is the use of cover sheets with irregular shapes which lead to the overlapping of sheets when the wind speed becomes faster. In addition, the previous studies have not mentioned the effect of wind speed on the proposed cover systems and how they could cope with such a problem. Fortunately, such weaknesses have been overcome during the application of the proposed technique.

The new technique is based on the concept that the evaporation can be reduced from open water surface using floating cover sheets.

The Percent Coverage of Water Surface

Different geometric shapes (triangular, trapezoidal, square, irregular, circular, and rectangular) for the cover sheets were studied to find the best one which gives the maximum percent coverage and permits oxygen exchange between air and water. The most suitable shape achieving the maximum coverage and permitting sunlight penetration through water is the circular one.

Kind of Cover Material

Different coverage materials were subject to experimentation and comparison as far as their ability to reduce evaporation from open water surfaces and their durability and cost are concerned. These materials were, for instance, the waxen texture sheets, polystyrene, foam, foamed rubber, perlite ore, plastic sheets, poly laminated plastic, polystyrene beads and polystyrene rafts. It is proven that the most suitable material is the foam sheets.

Control of Wind Effect on Cover Sheets

In order to ensure that no damage will befall or happen to the covering foam sheets because of the wind, a safe fixing system is proposed. It is a pontoon made up of different components as follows (Fig. 10): Floating frame made of Wooden or PVC cross sections, a trash rack, mooring point, chain and concrete anchorage block.

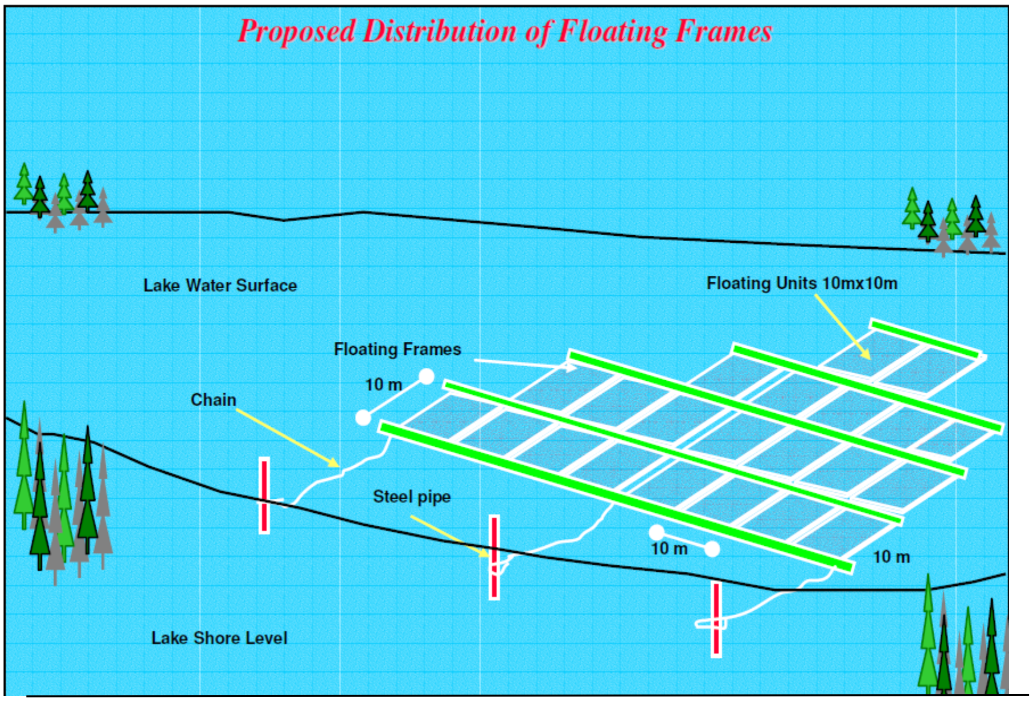

Figure 10. The proposed distribution of floating frames (Pontoon)on the lake surface

(SOURCE) Eleventh International Water Technology Conference, IWTC11 2007 Sharm El-Sheikh, Egypt

Conflicts of Interest: The authors declare no conflicts of interest.

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