

QUANTIFYING THE INFLUENCE OF SINKHOLES ON WATER BALANCE IN IRAN'S GOLGIR ALLUVIAL PLAIN

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Abstract. Southwestern Iran's Golgir plain lies on chalky bedrock made up of Tertiary gypsum surrounded and covered by thin Quaternary deposits. Since the onset of the new millennium, this region and its farmland has been prone to land depression and other instability phenomena linked to gypsum dissolution. A simple water balance over the period of 2005 to 2012 was employed to assess the role of sinkholes in these phenomena. Geological and geophysical features as well as initial water balance calculations confirmed the presence of sinkholes and their influence in the study area. A significant discrepancy ($2.55 \times 10^6 \text{ m}^3$) was observed between annual estimates of water inputs and discharge from the region, likely attributable to errors in identifying and quantifying output components. A bedrock map derived from geophysical investigations and the geological characterization of the chalky bedrock showed that, in comparison to the local groundwater table, there was a roughly 40 m drawdown towards the location of sinkholes. Groundwater inflow towards the aquifer was revised so as to include an identified sinkhole output component in the water balance equation, resulting in a much greater accuracy in the annual water balance estimates. Estimated annual recharge volumes ranged from 4.39×10^6 to $7.15 \times 10^6 \text{ m}^3$, with a mean of $5.64 \times 10^6 \text{ m}^3$. The water balance equation was shown to constitute a simple, cost-effective, and reliable approach to the recognition and evaluation of sinkholes in areas under similar conditions.

Keywords: *chalky bedrock, groundwater recharge, hydrogeology, sinkhole, water management*

Nomenclature

A	Area of the aquifer
m ³	Cubic meter
mm	Millimeter
ESL	Envelope Straight Line
GIS	Geographic Information System
I _G	Subsurface input water from aquifer boundaries
I _{IRF}	Infiltration volume from irrigation return flow
I _P	Infiltration volume from precipitation
I _R	Infiltration volume from runoff
I _{SW}	Infiltration volume from industry and domestic wells
O _D	Output volume from the aquifer system by drainage into the river
O _{Sh}	Output volume from the sinkhole
O _{ET}	Output volume from the aquifer system by evapotranspiration
O _G	Subsurface output water from aquifer boundaries
O _W	Output volume from the aquifer system by well pumping
PET	Potential of evapotranspiration
Sy	Specific Yield
WBE	Water Balance Equation
ΔH	Changes in groundwater level
ΔS	Changes in saturated groundwater storage
ΣI	Sum of the Input Components
ΣO	Sum of the Output components

Introduction

Given its pivotal role as a major water resource in arid and semiarid regions, groundwater is of particular concern to such regions' water resource managers and hydrogeologists, both in terms of their quality and availability (Jiang et al., 2009; Bain et al., 2014). In arid and semiarid regions, such as Iran, groundwater is considered one of the few reliable resources of water available to communities where population growth and intense water usage result in water scarcity, particularly of drinking water (Girman et al., 2007).

Different portions of gypsum deposits are characterized by a variety in lithological composition (e.g. Testa and Lugli, 2000; Gündogan et al., 2005; Schreiber et al., 2007) and texture (e.g. Gündogan et al., 2008; Hildyard et al., 2009). The complexity of alternating gypsum, limestone, sand, gravel and clay layers, as well as the presence or absence of an intergranular matrix is the result of both chemical and physical conditions of the evaporitic sites of deposition, and the subsequent diagenetic mineral transformations mediated by tectonics, burial, exhumation and weathering processes (Festa et al., 2016).

Depressions or outright holes in the surface of alluvial terrain, sinkholes occur when soils or other surface deposits overlying karstic rocks collapse into conduits enlarged by dissolution (Soriano and Simon, 1995). A number of factors may operate in concert in the development of alluvial sinkholes, amongst which Soriano and Simon (1995) distinguish three main groups: physical (substrate solubility, lithology and land cover), hydrological (water infiltration, hydraulic gradient, depth and seasonal variations of the water table, chemical composition of groundwater) and human factors (irrigation, pumping, construction). These factors' influence on sinkhole formation occurs primarily through either:

- (i) the evacuation of material through the subsoil, a process tied to infiltration rate, subsurface flow and chemical composition of water, bedrock solubility, and the capacity for movement of sediment-sized particles, or
- (ii) the probability of collapse or subsidence of the cover, a process tied to lithology, geomechanical behaviour, as well as water table depth and fluctuation.

The ability of a water balance equation (WBE) method to reveal and quantify unknown components of the hydrological cycle (e.g., sinkholes, faults, leaky layers, boundaries) in a high-evaporation setting, allows the development of accurate WBEs for (semi-)arid zone aquifers or plains with localized pockets of gypsum. Such pockets in the bedrock of a plain or aquifer call for novel groundwater modeling and WBE analysis, along with a good knowledge of subsurface conditions beneath the plain or aquifer, to determine and implement an appropriate and well-informed on-site remedial action and estimate its overall cost.

Typically, a few destructive boreholes are drilled, a geophysical study is undertaken and on occasion a few soil samples are also analyzed, offering WBE studies to have the potential to accurately simulate subsurface water recharge/discharge. Among the existing methods, WBE methods along with geophysical studies and analyses of borehole exploration logs are the most promising.

A basic mass balance equation widely used for quantifying groundwater recharge, the WBE constitutes one of the most basic methods in water resources management and hydrology. The WBE's water balance/budget considers strictly the volumes of water present at the outset, entering and leaving a regional- or local-scale three-dimensional space during a specific period of time (Fabbri et al., 2016). While tracer techniques,

numerical models, and hydrological budgets can be used in water balance management, the simple water balance, while the most basic of methods, can provide fairly acceptable results. Other approaches may prove to be complex, time-consuming, or draw on data requiring sophisticated acquisition methods, making them a less than optimal approach for managers and hydrologists in the field (Manghi et al., 2009). One of most widely employed yet simplest methods of evaluating the groundwater budget is the water balance equation (WBE). The accuracy and the relevance of conclusions drawn through a WBE approach greatly depend on the accuracy of water balance components used in this method.

The water balance method applied in the present study is supported by the principle of conservation of mass (of water), as defined by the continuity equation given by Sokolov and Chapman (1974). In general, management and decision-making regarding the different water resource fractions of groundwater, surface water, and changes in groundwater storage are strongly dependent on the results of water balance analysis in an aquifer or basin (Todd and Mays, 2005).

By examining different water budget components, we can discover that irrigation may, for example, be the component most influential to aquifer recharge (Fabbri et al., 2016). Therefore, determining the levels of recharge and discharge of groundwater, as well as other effective factors on groundwater balance play a significant role in groundwater resources management, especially in semiarid areas such as Iran (Jafari et al., 2012; Lin et al., 2013).

The methods chosen in estimating and studying groundwater recharge (Scanlon et al., 2002), a critical component in the water balance, depends on the desired accuracy of the results, data availability and the complexity of the hydrogeological system (Wendland et al., 2007; Chenini and Kouzana, 2016). The methods range from simple analytical water balances to more complex numerical models (Wendland et al., 2007; Narasimhan, 2008; Manghi et al., 2009; Rayburg and Thoms, 2009; Calderhead et al., 2012; Praveena et al., 2012; Cao et al., 2013; Bocanegra et al., 2013; Wen et al., 2013; Mollema et al., 2013; Park et al., 2014; Maruyama et al., 2014; Mohammadi et al., 2014; Željkočić and Kadić, 2015; Tóth et al., 2016). Employing a mass-balance methodology, Portoghesi et al. (2005) developed a geographic information system (GIS) model to estimate groundwater recharge in poorly gauged environments. Joodavi et al. (2016) evaluated groundwater recharge from hydrogeological inflow (e.g., infiltration, return flows and precipitation) in a complex alluvial-karst system. Raneesh and Thampi (2013) implemented the WBE in applied groundwater recharge models to quantify changes in groundwater level and water balance components. In a key study undertaken in southern Iran, Mohammadi et al. (2014) assessed groundwater recharge in a semi-arid system by using WBE to investigate the role of the Burazjan fault. They concluded that WBE constitutes an appropriate and sufficient approach to quantify known and specific unknown water balance components.

In the present study, a WBE approach took into account the role of local geology (e.g., chalky sinkholes in the alluvial sediments of the lower portion of the Golgir plain) along with that of the natural annual recharge of the alluvial aquifer. The study considered whether the presence of extraneous factors (e.g., sinkholes) influenced groundwater recharge or discharge in the Golgir plain. To our knowledge, this constitutes the first effort to employ a WEB as a simple, cost-effective, and easy-to-apply approach to quantifying the role of sinkholes as an output component.

Study Area

Located in southwestern Iran near the city of Masjed Soleyman, the Golgir plain (Fig. 1), with an expanse of $\approx 25 \text{ km}^2$ situated between $49^\circ 26' 45''\text{E}$ – $49^\circ 32' 33''\text{E}$ lat. and $31^\circ 43' 20''\text{N}$ – $31^\circ 47' 12''\text{N}$ long., is the country's largest plain and alluvial aquifer. Elevations on the Golgir plain range from 246 m–390 m AMSL. The villages of Golgir, Bahramabad, Mohammadabad, Valyabad Sabzabad and Shamsabad are the most important towns on the plain.

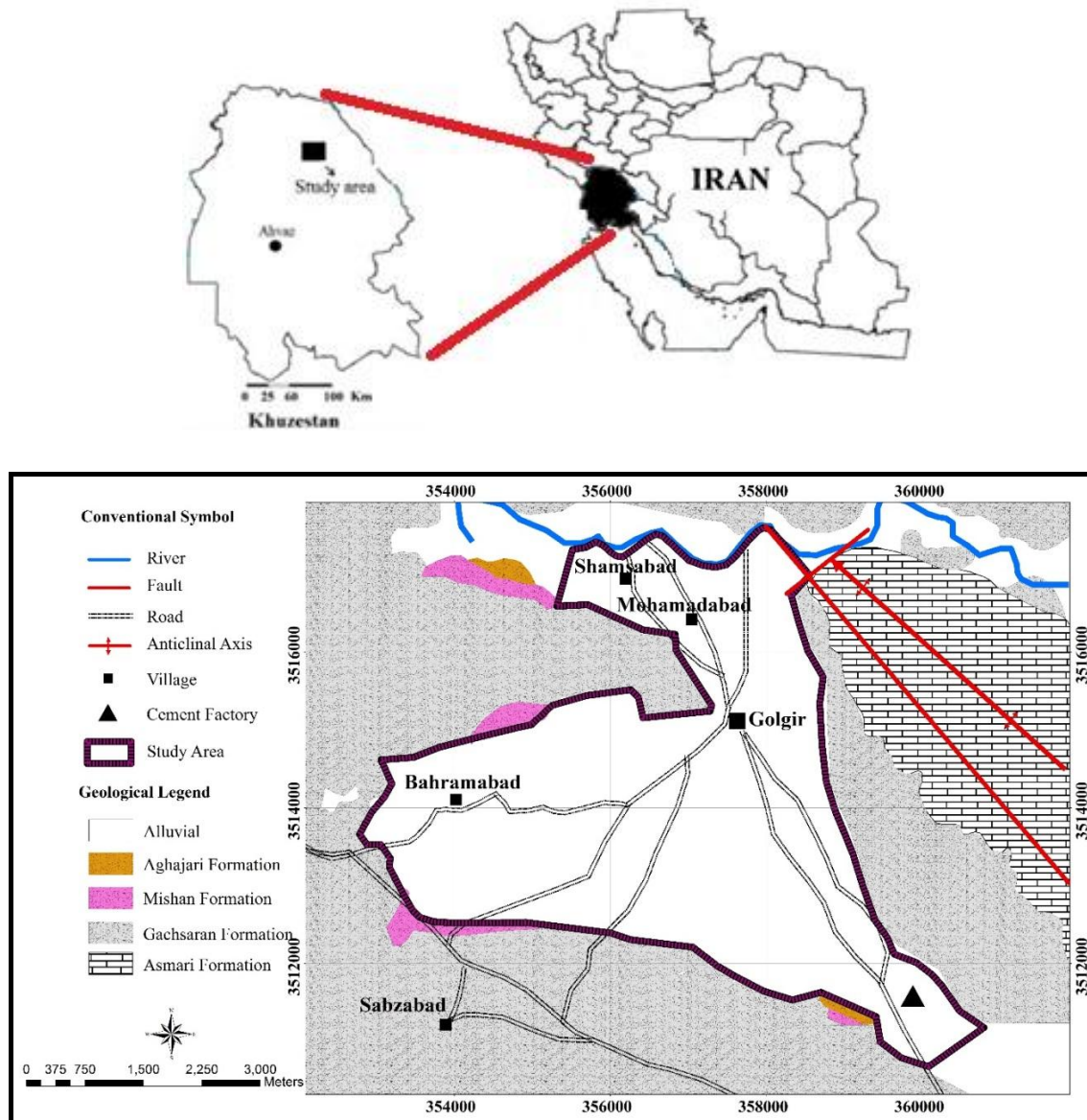


Figure 1. Geographic and geologic map of study area (Golgir plain, Iran)

The study area's climate is generally semi-arid, with dry summers and mild winters. Between 2005 and 2012, the annual mean maximum and minimum temperatures were 38° and 12° C, respectively, while annual mean precipitation and evaporation were 320 mm and 518 mm, respectively (Ahvaz IRIMO, 2013).

The Golgir region is an alluvial plain created predominantly by the erosion of the surrounding Asmari and Gachsaran formations which border the plain to the east and west, respectively. In general, the presence of chalky deposits in alluvium resulted in increased concentrations of sulfate and total dissolved solids in groundwater. The Gachsaran formation, which contributes the bedrock beneath the Golgir plain, bears anhydrite materials and chalky material, the latter of which contributes to the formation of active sinkholes which can act as water discharge sinks. The sinkholes presently active in this region causes a number of problems both in farming activities and groundwater management. For example, farmers lose water from extraction wells and attempt to replace it by increasing the well depth. In the study area, groundwater management issues became critical at the onset of the new millennium, with important damage being observed in the regions' extraction wells, farmland and roads.

Geological Framework

The study area is located in the Zagros Orogen, one of Iran's five structural zones (Alavi, 2004). Topographic maps, aerial photographs, geological maps (obtained from Khuzestan Department of Water and Power, 2013), field studies and Landsat ETM⁺ satellite images (obtained from Usgs, 2013) were used to investigate the study area's geological characteristics. The Pabdeh formation (Oligocene-Eocene), the oldest formation in the region, includes shale, blue and dark green marls, along with a variety of thin layered clay limestone in its upper profile (Darvishzadeh, 1991). In the study area, the Pabdeh formation acts as a basement of karstification for the Asmari formation (Oligocene-Eocene). The Asmari formation consists of layers of soft, cream-colored limestone.

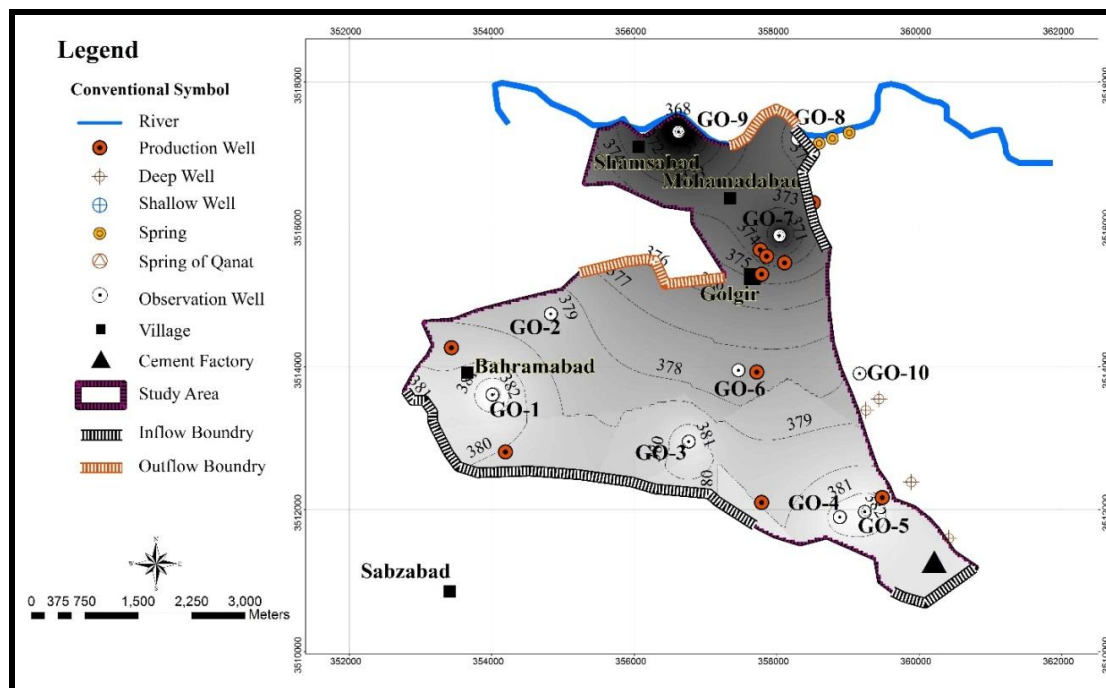


Figure 2. Hydrogeological and water resource map in Golgir plain, Iran

The majority of precipitation infiltrates through a highly fractured zone into the karstic system. Contributing to a loss in groundwater quality in the study area, the Gachsaran formation (Miocene), which surrounds the Golgir plain to the North, South and West, consists of salt, anhydrite, colored-marls, limestone and some bituminous shale. Overall, the plain is surrounded by Asmari, Gachsaran, Mishan, and Aghajari geological formations. A hydrogeological and water resource map of the Golgir plain (Fig. 2), shows the general groundwater flow direction in the plain to be from the South and Southwest to the East and North, with the groundwater outlet located North of the plain.

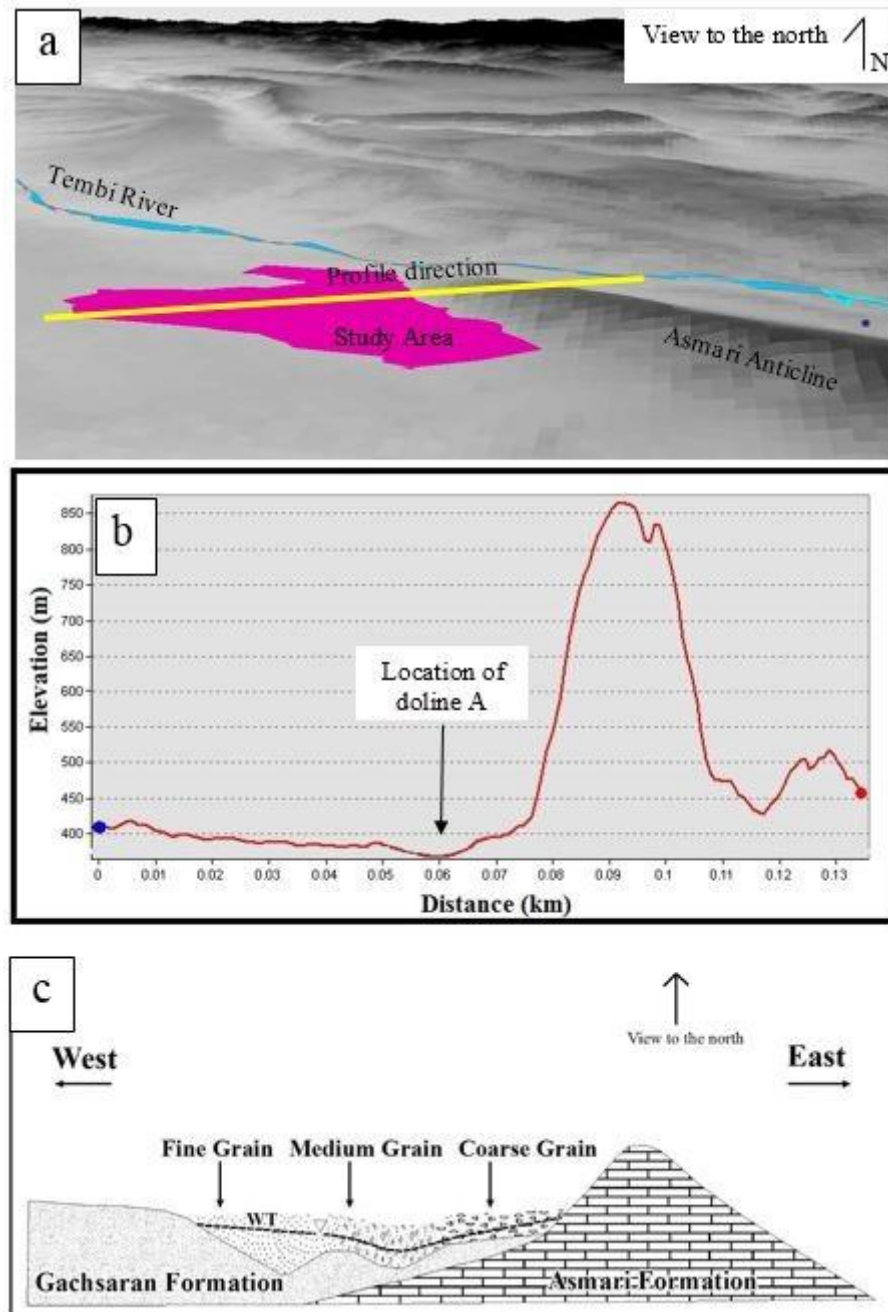


Figure 3. a) Digital elevation model image b) Location of sinkhole A in profile direction c) The schematic cross section of sedimentation process in the alluvium of study area (Golgir plain, Iran)

Erosion of the Asmari formation has caused sedimentation in the form of gravel deposits along with some clay. Drilling logs show that as one moves away from the Asmari anticline from East to West, the volume of fine-grained sediments from erosion of the Gachsaran formation increases. Digital elevation model images, profile direction, and a schematic cross section of sedimentation process in the Golgir plain are presented in *Fig. 3*. Erosion of the Gachsaran formation caused increased deposition of silt and clay deposits and also led to the presence of sulfated minerals in the Golgir plain's alluviums.

Hydrogeological Framework

With a basin extending over roughly 2586 km², the Temby (Shoor) River is the only river in the study area. Given its mean electrical conductivity (EC) of 25 mS cm⁻¹, the Temby River's waters are practically unusable given their salinity. The study area includes two aquifers: (i) one of hard rock (limestone), composed of the Asmari formation and situated in the Asmari anticline, which extends roughly 27 km across the eastern portion of the Golgir plain and (ii) one alluvial, composed of limestone debris from the Asmari formation and plaster debris from the Gachsaran formation. The main sources of recharge are infiltration from precipitation, irrigation return flows and boundaries of the alluvial aquifer.

Evidence from the surface of the Asmari anticline indicates the development of karstification in the Asmari limestone aquifer. This alluvial aquifer ranges from 10 m to 100 m in thickness, with the greatest thickness occurring in the Southeastern portion of the plain. Eight years of monthly groundwater levels at 10 observation wells and piezometers were used in present study (Khuzestan Department of Water and Power, 2013). Hydraulic conductivity ranged from 1 m d⁻¹ to 7 m d⁻¹, while the specific yield (volume of aquifer water released from storage per surface area of aquifer per drop in the water table; m³ m⁻² m⁻¹ — Neuman, 1987; Todd and Mays, 2005) ranged from 0.08 to 0.20.

Theoretical Background

The present study drew upon different data sources: surface observations of alluvial sinkholes (e.g., farmland depressions and sites of road subsidence), observations of outcrops on derelict depressions, a detailed cartography of variations in the Golgir plain over active sinkholes, as well as a compilation and analysis of physical and hydrological data.

The development of alluvial sinkholes is influenced by a number of factors (Soriano and Simon, 1995, 2002): (i) groundwater discharge through the bedrock (e.g., solubility, presence of penetrable coarse-sized particles, infiltration and flow), and (ii) the probability of subsidence of the cover as a result of groundwater discharge from the study area (e.g., lithology, geomechanical behavior, depth of the water table).

After reviewing the available information, evidence must be examined and gathered to identify alluvial sinkholes (i.e., the unknown component) by means of assessing their impact on the hydrogeological system. This can be done by: (i) using geophysical maps of the bedrock (*Fig. 4*), (ii) monitoring sudden changes in groundwater discharge in the wells, especially in the vicinity of alluvial sinkholes, (iii) noting the presence of a chalky rock basement prone to forming sinkholes (*Fig. 5*), (iv) noting sudden collapses of the bedrock on the order of 40 m, (v) identifying the region's structural geology and

how prone the region is to the formation of sinkholes, and (vi) noting drops in groundwater levels in piezometers and observational wells in the vicinity of alluvial sinkholes compared to other parts of the plain.

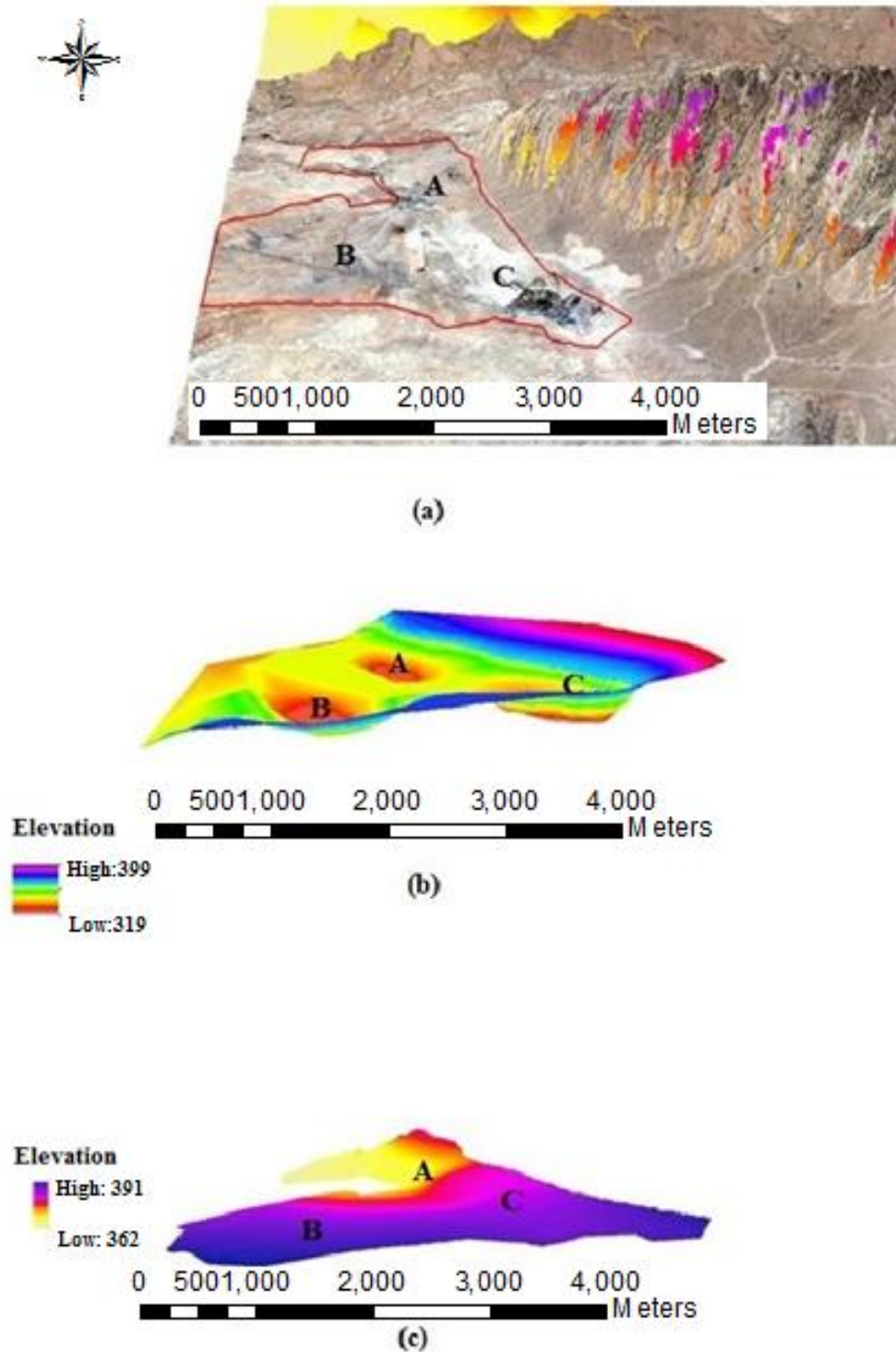


Figure 4. Three-dimensional images of bedrock and groundwater level in Golgir plain, Iran:
a) 3D Satellite image b) geophysical map of bedrock c) groundwater level



Figure 5. Sinkhole in the Gachsaran formation in Golgir plain, Iran

By studying fluctuations in groundwater level, groundwater level depression and logs of exploration wells located within the area of alluvial sinkholes (*Fig. 6*), the existence of clay in the alluvial deposits was confirmed. The existing clay in the alluvial deposits influences sinkhole activity in the subsoil through its control on the permeability of the cover. *Fig. 6*, shows that clay content within the alluvial sediments varied from about 5% in sinkhole A (Asmari formation sediments, lime debris and some sand), to 80% in sinkhole C (Gachsaran formation sediments, silt and clay). The area within sinkhole A, which showed the greatest sinkhole development coincided with the area bearing the least clay; therefore, the development of sinkholes in the region is clearly greater in regions with lesser clay content. The sudden decrease in the level of groundwater at sinkhole A seems to have mainly been caused by the output component (i.e., the sinkhole). The existing clay in the sedimentary sequence of alluvial sinkholes B and C, rendered these sinkholes inactive and closed water flow pathways.

Chalky alluvial sinkholes in the Golgir plain can be considered as a simple output component; therefore, application of the WBE can be effective in determining their role and hydrological performance. The plain's actual recharge, calculated incorrectly in prior studies due to a lack of knowledge can be corrected through a WBE-based assessment of sinkhole performance. However, before choosing a suitable method for the determination of groundwater recharge, many factors must be considered. Depending on data availability, the hydrological system in question, and the desired accuracy of results, several methods exist to estimate groundwater recharge (Scanlon et al., 2002; Wendland et al., 2007; Batelaan and DeSmedt, 2007). The first step in estimating groundwater recharge was to provide a basic conceptual model of the Golgir plain study area, allowing a better understanding of its hydrogeological behavior and water balance.

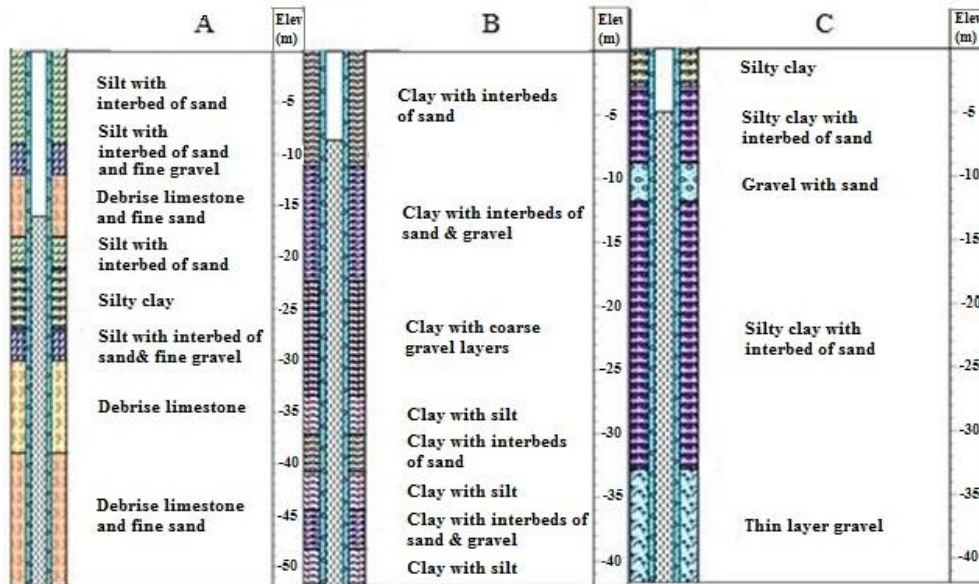


Figure 6. Exploration well logs located within the area of sinkhole

McWhorter and Sunada (1977) defined the overall WBE as follows:

$$(\Sigma I - \Sigma O) \Delta t = \pm \Delta S \quad (\text{Eq.1})$$

where ΣI and ΣO are total input and total output from/to the aquifer, respectively, over a duration Δt , and where ΔS is the change in groundwater storage. The input and output components involved in the calculation of the balance for a given aquifer are:

$$\Sigma I = I_p + I_r + I_{IRF} + I_{sw} + I_G \quad (\text{Eq.2})$$

and

$$\Sigma O = O_w + O_{ET} + O_G + O_D \quad (\text{Eq.3})$$

where, I_p , I_r , I_{IRF} and I_{sw} are the infiltration volume from precipitation, runoff, irrigation, and from industry and domestic wells, respectively, and O_w , O_{ET} and O_D are outputs from the aquifer system arising from pumping, evapotranspiration and drainage into the river respectively. The parameters I_G and O_G are, respectively, the subsurface input and output of water from the aquifer boundaries. After determining the input and output components in the above equations, changes in groundwater storage (ΔS) can be calculated as (Bredehoeft et al., 1982):

$$\Delta S = \Delta H \times A \times S_y \quad (\text{Eq.4})$$

where ΔH is changes in groundwater level over a duration Δt , A is the area of the aquifer and S_y is the specific yield of the aquifer. The groundwater balance can then be

calculated, with the total recharge and discharge to/from the aquifer calculated by splitting Eq. 1 into two equations:

$$\Sigma O = (I_P + I_R + I_{IRF} + I_{sw} + I_G) \pm S \quad (\text{Eq.5})$$

$$\Sigma I = (O_w + O_{ET} + O_G + O_D) \pm S \quad (\text{Eq.6})$$

These equations to estimate ΣI and ΣO can then serve: (i) in calculating the output or input components is particularly difficult, and ii) when the region's hydrogeology must be taken into consideration.

Results

Applying the WBE allows an effective identification of components in the water balance (Eq. 1), but necessitates the calculation of the input and output components of groundwater along with changes in groundwater storage, as well as sufficient understanding of the conceptual model and components affecting the Golgir plain's water balance. Faced with the Golgir plain's hydrologic and geological complexities, and the need to draw out information regarding the performance of the plain's flow components, the effective components of input/output flows as well as changes in groundwater aquifer storage were calculated.

Output components (ΣO)

Data collected between 2005 and 2012 led to an estimate of the mean annual volume of water drawn from 18 extraction wells to be about $1.81 \times 10^6 \text{ m}^3$ (Table 1). To calculate the volume of water lost at the aquifer boundaries, Darcy's equation (Eq. 7), was used:

$$V = TLI\Delta t \quad (\text{Eq.7})$$

where the parameters T , L , I and Δt represented transmissivity of the aquifer, the length of the output aquifer boundary, the hydraulic gradient and the duration over which the water balance was assessed, respectively. In order to measure the hydraulic gradient and flow output boundary length, output boundaries were specified (Fig. 2). Monthly changes in groundwater level were then assessed using GIS. Flow output volume on an annual basis is provided in Table 1.

The evaporation from surfaces and transpiration from plants which occurs when sufficient water is available is termed potential evapotranspiration (ET_p), whereas actual evapotranspiration (ET_a) represents evapotranspiration under water-limiting conditions (Thornthwaite, 1948). Using the approach developed by Thornthwaite (1948), the study area's ET_a was derived from monthly mean temperature and rainfall on the Golgir plain, and an estimate of the water needed for the growth of the dominant plants in the study area (Shaw et al., 2010). The final ET_a values (Table 1) were calculated using the White Curve (White, 1932).

To determine the nature of the hydraulic interactions occurring between the river and the alluvial aquifer, field surveys and comprehensive studies were employed to determine the absence/presence and nature of such interactions. Analysis of field surveys, evidence from exposed springs, groundwater flow direction and satellite

images indicated that, due to fault action and the presence of a thick clay layer in the soil, there was no hydraulic interaction between the plain and the river reaches situated in the Eastern portion of the plain. However, in the western portion of the plain contiguous with the river, the river drains the aquifer. Groundwater level changes visualized using GIS were employed in calculating outflow from the Golgir plain to the river. The volume of groundwater seepage into the river between 2005 and 2012 was calculated on a monthly basis (Eq. 7). The final calculated output components (ΣO) ranged from $3.72 \times 10^6 \text{ m}^3 \text{ y}^{-1}$ to $5.94 \times 10^6 \text{ m}^3 \text{ y}^{-1}$, with an average of $4.78 \times 10^6 \text{ m}^3 \text{ y}^{-1}$ (Table 1).

Table 1. The value of output components ($10^6 \text{ m}^3 \text{ y}^{-1}$) for Golgir plain in 2005 to 2012

Δt (year)	O_G	O_W	O_{ET}	O_D	ΣO
2005	1.91	1.89	0.38	0.62	4.80
2006	1.89	1.87	1.19	0.58	5.53
2007	1.62	1.91	0.16	0.57	4.26
2008	1.43	1.75	0.38	0.55	4.11
2009	2.25	1.98	1.13	0.58	5.94
2010	1.47	2.01	1.27	0.55	5.30
2011	1.45	1.6	0.12	0.55	3.72
2012	2.07	1.5	0.41	0.63	4.61
Average	1.76	1.81	0.63	0.58	4.78

Changes in water storage (ΔS)

In order to calculate changes in groundwater storage, it was necessary to calculate ΔH and S_y (Eq. 4). Monthly groundwater levels in 10 observation wells were used in order to calculate the mean monthly groundwater level in the aquifer and assessed in ten sampling well-associated subregions of the plain developed in the GIS environment using Thiessen polygons. Monthly hydrographs of aquifer volume and rainfall depth over the study area (Fig. 7), served in calculating annual ΔH in the aquifer.

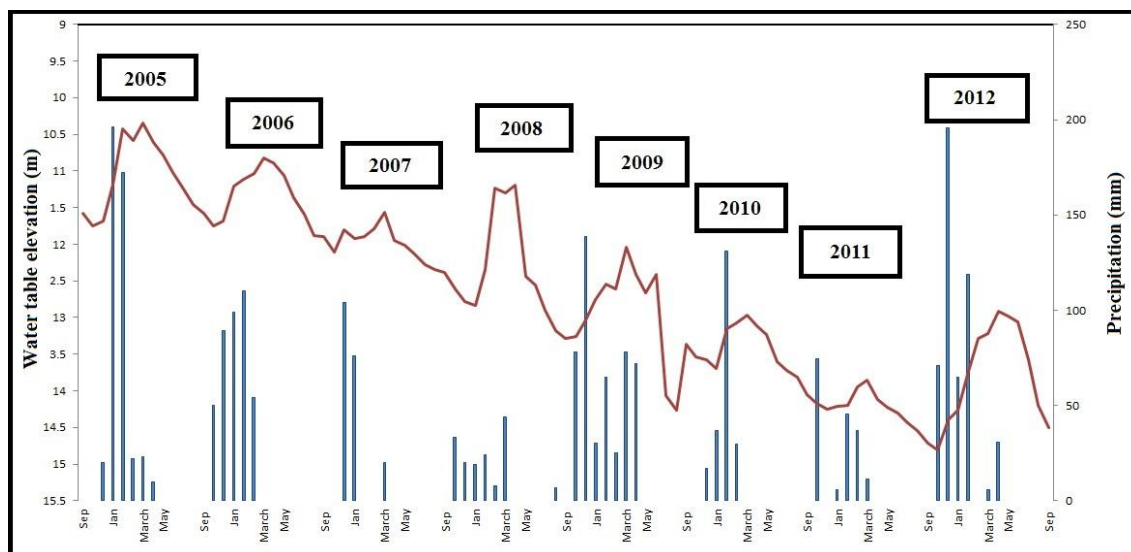


Figure 7. The hydrograph of aquifer and rainfall of study area (Golgir plain, Iran)

Due to the porous nature of the aquifer, determination of a comprehensive value for specific yield (S_y) is difficult (Manghi et al., 2009). Based on the work of Varni et al. (2013) who developed an “Envelope Straight Line” (ESL) method to estimate mean S_y values for the Pampa plain, an ESL method was used to obtain S_y in the present study. Given the strong and direct relationship between rainfall and groundwater recharge, S_y values can be estimated by drawing a plot of precipitation vs. rise in groundwater level. In the present study, a Thiessen polygon method separating the plain into 10 sampling well-associated subregions served to enhance the accuracy of the analysis and to aid in calculating the results. For each polygon, the rise in groundwater level was plotted against effective rainfall over the study period of 2005 to 2012, in an effort to determine S_y values for each polygon. The largest specific yield was estimated for polygon GO-8 ($S_y = 0.20$), and the lowest value for polygon GO-1 ($S_y = 0.08$), with an overall weighted mean of 0.13 for the whole plain. Values of ΔS from 2005 to 2012 obtained using Eq. 4, ranged from $-3.35 \times 10^6 \text{ m}^3 \text{ y}^{-1}$ to $0.16 \times 10^6 \text{ m}^3 \text{ y}^{-1}$, with a mean value of $-1.69 \times 10^6 \text{ m}^3 \text{ y}^{-1}$ (Table 2). Fig. 8 shows the relationship between effective rainfall and groundwater level rise across all polygons (GO-1 to GO-10).

Input Components (ΣI)

In order to calculate I_p , a double ring infiltration test was set up in three regions of the Golgir plain of known soil texture, and documented through satellite images and field surveys. Runoff was calculated based on the study of Mohammadi et al. (2014). The conceptual model used to determine the input (inflow to the plain) boundaries of flow and their length, along with I_G , was developed using the Darcy equation. To determine the input boundaries, a flow direction map and field surveys were carried out. The inflow boundaries were specified for two regions of the Golgir plain (Fig. 2). Agricultural return water flow, volume of water penetrating originating from industry and domestic wells, along with penetration percentage were estimated (Table 2). The ΣI was calculated to be within a range of $4.32 \times 10^6 \text{ m}^3 \text{ y}^{-1}$ to $7.15 \times 10^6 \text{ m}^3 \text{ y}^{-1}$, with an average of $5.64 \times 10^6 \text{ m}^3 \text{ y}^{-1}$.

Table 2. Estimated discharge ($10^6 \text{ m}^3 \text{ y}^{-1}$) in Golgir plain in the years of 2005 to 2012

Δt (year)	I_G	I_P	I_{IRF}	I_{SW}	I_R	ΣI	ΔS	ΣO
2005	3.56	1.86	0.22	0.79	0.07	6.50	-0.67	7.17
2006	3.46	1.69	0.23	0.80	0.07	6.25	-1.34	7.59
2007	3.11	0.84	0.20	0.77	0.03	4.95	-2.34	7.29
2008	2.66	0.65	0.20	0.79	0.03	4.32	-0.33	4.65
2009	3.66	2.04	0.22	0.79	0.08	6.79	-2.68	9.47
2010	2.86	0.90	0.20	0.79	0.04	4.78	-3.35	8.13
2011	2.47	0.73	0.24	0.92	0.03	4.39	-2.98	7.37
2012	3.84	2.05	0.25	0.94	0.08	7.15	0.16	6.99
Average	3.2	1.35	0.22	0.82	0.05	5.64	-1.69	7.33

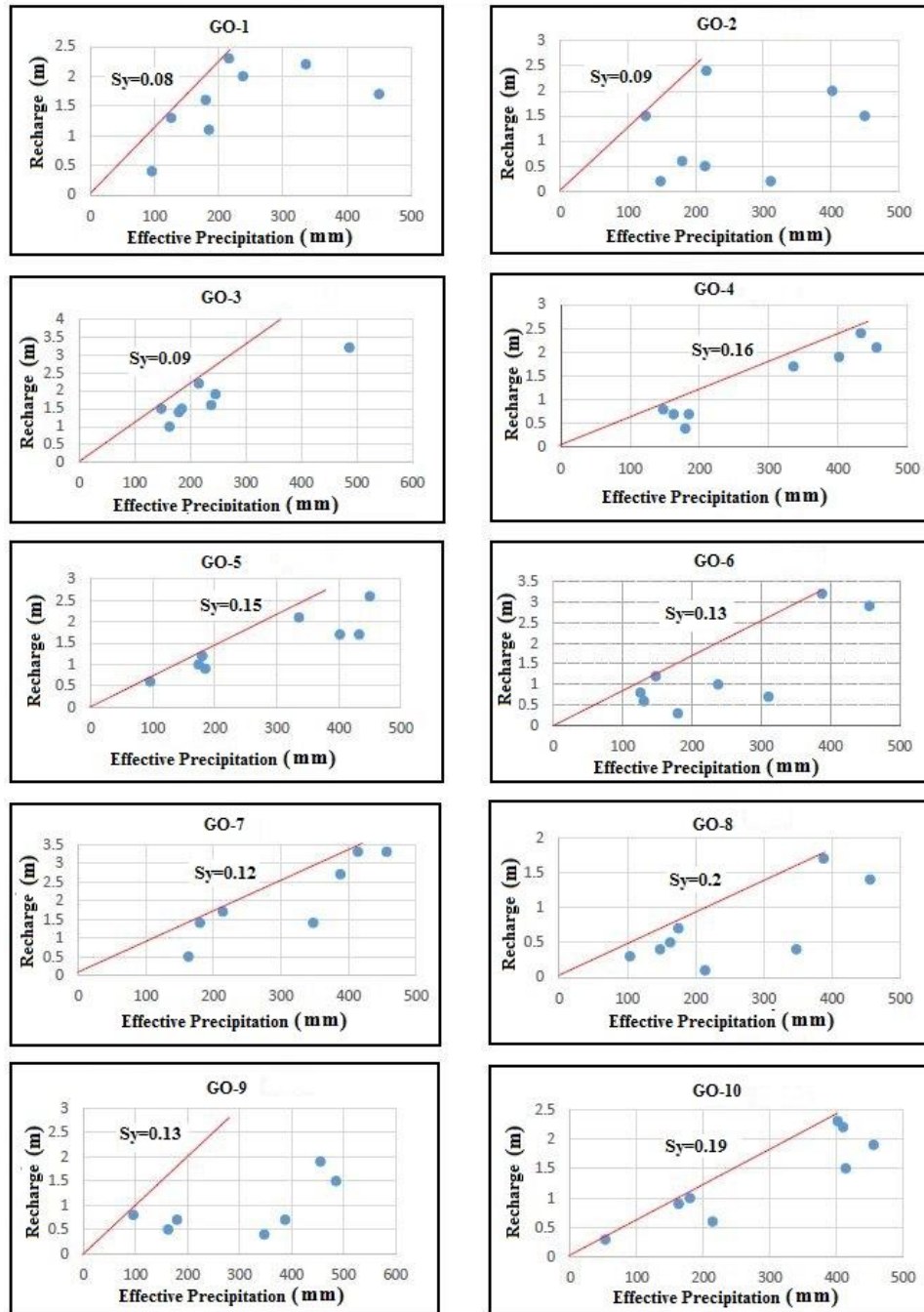


Figure 8. Relationship between effective rainfall and groundwater level rise

Discussion

The main objective of the present study was to evaluate the role of alluvial sinkholes in groundwater budget estimation using the WBE. The WBE indeed showed that there were unknown output components in the Golgir plain. With a greater understanding of the role of alluvial sinkholes and their output volume (O_{Sinkhole}), closer matches of water inputs and outputs were achieved in the WBE analysis, thereby minimizing underestimation errors or miscalculations of input components in estimating ground water recharge.

Given that from 2005 to 2012 $\Sigma I > \Sigma O$, the ΔS supported a plausible assumption that errors occurred in calculating changes in aquifer storage. This left three possible explanations: (i) underestimation or error in the calculation of output flow components (about 25%); (ii) overestimation or error in the calculation of flow input components, or (iii) a lack of understanding regarding unidentified output flow components. Comparing the ΣO obtained from Eq. 3, to that obtained with Eq. 5, showed a significant difference which averaged $2.55 \times 10^6 \text{ m}^3 \text{ y}^{-1}$ (Tables 1 and 2).

Direct measurement of most of the components of the WBE is impossible, difficult or expensive to implement given a lack of knowledge of the presence and magnitude of output flow components; therefore, these components are estimated using secondary variables. In practice, there can be an at least 20% error in the calculation of certain components (Mohammadi et al., 2014); though, based on the present calculation of ΣO , an error exceeding 20% should have occurred.

Evaluation of the effect of errors in the calculation and the determination of ΣO based on the WBE has been studied through sensitivity analysis (Hamby, 1994; Frey and Patil, 2002). Differential Analysis can be used to examine the effect of error in all components of the water balance, as well as on ΣO error, assuming ΣO to be dependent upon components of the WBE:

$$\Sigma O = f (I_S, O_W, O_G, O_{ET}, I_{IRF}, I_G, I_P, I_R, I_{SW}) \quad (\text{Eq.8})$$

Based on partial derivatives of ΣO with respect to each and all components, differential analysis evaluated the effect of each components in determining ΣO (Table 3). This method uses Taylor series to develop a sensitivity analysis (Helton, 1993; Helton and Davis, 2003):

$$Y(X) = f(x_0) + \sum_{j=1}^{xn} \left[\frac{\delta f(x_0)}{\delta x_j} \right] [x_j - x_{j_0}] \quad (\text{Eq.9})$$

where $Y(X)$ is model prediction, $f(x_0)$ base value function, $\delta f(x_0)$ base value function differential, x_j variable differential.

Table 3. Changes in terms of changes in the components of Eq. 5

Percent of error in component of Eq. 9	5	10	15	20	25	30	35	40	45
dOut flow ($10^6 \text{ m}^3 \text{ y}^{-1}$)	0.13	0.26	0.38	0.51	0.64	0.77	0.89	1.02	1.15

The calculated error for ΣO in the WBE was $0.51 \times 10^6 \text{ m}^3 \text{ y}^{-1}$, significantly lower than the average ΣO ($2.55 \times 10^6 \text{ m}^3 \text{ y}^{-1}$) (Tables 1 and 2). Given that the probability for the mean ΣO was stronger than for the derived ΣO , applying the average value of the output from the aquifer into the balance equation yielded a more balanced equation.

Based on the geology of the study area, a reduction in ΣO (Table 1) in comparison with ΣO (Table 2), one can conclude that the discrepancy in the output component relates to existing sinkholes in the plain's bedrock. In the Golgir plain in these situations, an output flow component called O_{Sh} must be added to Eq. 3. The discharge calculated using Eq. 5, is consistent with the assumption of the role of the sinkhole

output in the plain. The magnitude of addition of annual O_{Sh} necessary to add the water output from the sinkhole and establish equilibrium in the WBE was estimated to range between $0.54 \times 10^6 \text{ m}^3 \text{ y}^{-1}$ and $3.53 \times 10^6 \text{ m}^3 \text{ y}^{-1}$, with an average of $2.25 \times 10^6 \text{ m}^3 \text{ y}^{-1}$ (Table 4). Comparison of O_{Sh} with other output components of the recharge process highlights the important role of sinkhole outputs in the Golgir plain's bedrock.

Table 4. The estimated value ($10^6 \text{ m}^3 \text{ y}^{-1}$) of output from the plain by using Eq. 3 and Eq. 5

Δt (year)	Result of Table 3	Result of Table 1	O_{Sh}
2005	7.60	4.80	2.37
2006	7.45	5.53	2.06
2007	7.05	4.26	3.03
2008	4.62	4.11	0.54
2009	9.19	5.94	3.53
2010	7.78	5.30	2.83
2011	7.03	3.72	3.65
2012	7.00	4.61	2.38
Average	7.22	4.78	2.55

Conclusions

The main objective of the present study was to assess the role of alluvial sinkholes in estimations of the groundwater budget using a WBE. The application of WBE to estimate net groundwater recharge and the recognition of other components affecting on groundwater discharge resulted in the heightened calculation accuracy. Calculation of the WBE in each year showed significant differences between: (i) the sum of known components of output flow and (ii) the sum of recharge and changes in groundwater storage. In general, the differences in the calculated values for groundwater output from sinkholes was estimated to be in a range of $0.54 \times 10^6 \text{ m}^3 \text{ y}^{-1}$ to $3.53 \times 10^6 \text{ m}^3 \text{ y}^{-1}$, with an average of $2.55 \times 10^6 \text{ m}^3 \text{ y}^{-1}$. Assuming the acceptability of some error in the calculation of recharge components and changes in groundwater storage, there remained two debatable issues: (i) errors in the calculation of the output components, and (ii) the role of unknown output components (e.g., alluvial sinkholes). Geological and hydrogeological evidence in the study area's bedrock confirms the presence of sinkholes and their significant role in sharp drops in the groundwater table. Finally, the net recharge of groundwater from 2005 to 2012 was estimated to be $4.39 \times 10^6 \text{ m}^3 \text{ y}^{-1}$ to $7.15 \times 10^6 \text{ m}^3 \text{ y}^{-1}$, with an average of $5.64 \times 10^6 \text{ m}^3 \text{ y}^{-1}$.

The WBE could therefore be consider as an easy to apply, reliable and cost-effective approach to ascertaining the nature of unknown components of the groundwater budget (e.g., sinkholes) in developing countries, where available data are somewhat limited.

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