THE ESTIMATION OF GROUNDWATER EXCHANGE IN AYDARKUL–ARNASAY LAKE SYSTEM BY A LAKE WATER BALANCE MODEL

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In this paper, a unique lake water balance (LWB) has been proposed as a key component for the sustainable groundwater (GW) management in arid/semi arid region, particularly in Aydarkul-Arnasay Lake System (AALS), Uzbekistan. The uniqueness of LWB here is by incorporating GW distribution and its interaction. Meanwhile, the evaporation is also locally trimmed for arid/semi arid area. It is a monthly-based calculation by introducing the lake surface area as function of observed lake water level. The result shows that from March to July, GW recharge is higher than GW discharge as indicated by positive GW-exchange ranging from 0.13 to 0.83 km^3/month. From August to February, GW discharge is higher than GW recharge (a negative GW-exchange). It's about -0.05 to -0.51 km^3/month. Verified with the observed data, this approach seems to serve as a reliable method for the reconstruction of GW-exchange into/out from the lake as well as useful information towards the sustainable GW management.

Key Words*: groundwater exchange, Aydarkul-Arnasay Lake System, lake water balance, arid/semi arid area.*

1. INTRODUCTION

Groundwater resources are considered as one of the important sources of freshwater in arid and semi-arid areas. A basic problem in arid areas, which often cannot be solved easily with conventional hydrological techniques, is to determine whether a given body of groundwater is actively recharged, i.e. whether it is a renewable resource.

There are several approximations to predict groundwater recharge/discharges into water bodies. Most of them include water balance that captures into account the meteorological data and land surface variables such as soil moisture and land cover types (Finch)[1)]. However, to gain better results then the local site-characteristics, that may differ from commonly used scientific approaches, should be carefully adopted in the determination of Lake Water Balance (LWB) components (Shaw)[2)].

Another one is by utilizing the hydraulic-head surface map coupled with boreholes, the water level assessment through GIS techniques application (Salama *et al.*)[3)]. This approach sounds very costly and relies on the existence of borehole data. It is difficult to be carried out under precise hydrologic environment, particularly where the depth of the aquifer is large. Groundwater tracers such as ^{222}Rn and ^{226}Ra have also been greatly used to determine groundwater flows even though they cannot give precise quantification (Hussain *et al.*)[4)].

In assessing groundwater movements, the most common way is by counting the quantities of the net-groundwater flow (the distinction between groundwater inflow and leakage) as a unique unknown variable in the water budget equation (Lee and Swancar)[5)]. Numerous lake hydrologic investigations regarding the net-groundwater flow has been reported (e.g. Krabbenhoft *et al.*[6)], Al-Weshah[7)], Motz *et al.*[8)] and Chikita *et al.*[9)]). Nevertheless, these kinds of works are extremely expensive and labor detailed seeing that lots of hydrogeologic, as well as water quality information or groundwater inspection boreholes are needed.

In arid/semi-arid areas, the water level and surface area of lake are highly sensitive to the climatic variables. In this situation the lake water level fluctuations becomes excellent indicators of drought/wet conditions changes. Moreover, it is an important measurable element of LWB.

The objective of this study is to estimate the groundwater exchange by a LWB approach. The uniqueness of the proposed LWB here are; (1) has been specifically setup to arid/semi arid area; (2) by incorporating the groundwater distribution and its interactions; (3) evaporation formulation is trimmed for arid/semi arid area; (4) dynamic monthly-based calculation by introducing the lake surface area as function of observed lake water level.

Results have been provided a reliable reconstruction of groundwater exchange into/out from the lake. Since this study is the first effort to study groundwater in this area, it delivers a very useful information for the researchers and local policy makers towards the sustainable groundwater (GW) management of Aydarkul Arnasay Lake System (AALS), Uzbekistan.

2. STUDY AREA

AALS constitutes lakes of Aydarkul, Arnasay, Tuzkan and surrounding desert territories. It is located at south-western part of Uzbekistan, as shown in **Fig.1**. In the north it is bounded by the Kyzylkum sandy desert while in the south by the foothills of the North-Nuratau Mountains and massive territories of Mirzachuli (Golodnaya steppe) in the east. The total length of east to west of the AALS is about 300 km and its north to south width ranges from 30 to 50 km[10),11)].

3. DATA AND METHODOLOGY

The data of groundwater level at observed wells (**Fig.1**), lake water level, rainfall, inflow from Chardara Reservoir and drainage network, climatology data (air temperature, wind speed and water vapor pressure) as well as topographical (*morphometric*) data for the past years were obtained from the Research Institute of Hydro-Meteorology of Uzbekistan[12)].

In the general form, the LWB is written as:

$$\Delta S = \Delta Inflow - \Delta Outflow \qquad (1)$$

$$\Delta S = I + R \pm GW_{ex} - E - O_{Irr} \qquad (2)$$

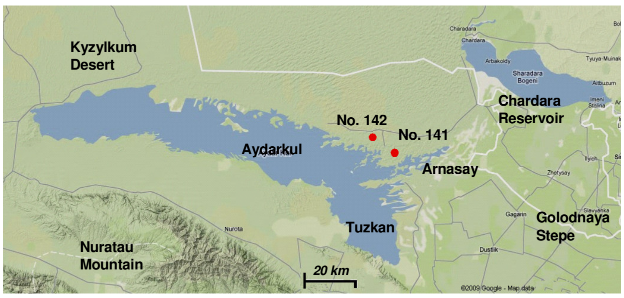

Fig.1 Map shows location of AALS, observed groundwater level (well No. 141 and No. 142) and lake's boundaries.

where,

- ΔS = change in lake water volume (km^3),
- I = inflow from Chardara Reservoir and the drainage network (km^3),
- R = direct rainfall onto lake surface (km^3),
- GW_{ex} = groundwater exchange with lake [can be positive (+) or negative (–)] (km^3),
- E = evaporation volume (km^3). The volume of evaporation is determined by multiplying the evaporation rate with surface water area of the lake (A) as function of water level (Sri Wahyuni *et.al*)[13)]. The adoption of local evaporation formulation will be discussed detail in the results and discussion,
- O_{Irr} = Outflow for irrigation (Arnasay Lake) (km^3).

Commonly, the groundwater discharge/recharge into/out from the lake is represented by groundwater exchange. It is being assessed by re-arranged eq.(1) into below formulation:

$$GW_{ex} = I + R - E - O_{Irr} - \Delta S \qquad (3)$$

Then they are quantitatively verified with the observed fluctuation of groundwater level nearby the lake.

4. RESULTS AND DISCUSSION

(1) Inflow from Chardara Reservoir

The main inflow of AALS is the abundance released water from Chardara Reservoir to the downstream part of the Syrdarya River (**Fig.2**). It is available from January to April when Chardara Reservoir can not release water into the downstream part of Syrdarya River due to ice jams at the lower part of the Syrdarya River. In the period of 1993 to 2006, the inflow varied from 0.00–3.22 km^3/month (0.34–9.29 km^3/year). The average of annual inflow was about 2.76 km^3 or 67% of the total inflow of AALS. The inflow during the cultivation season (April to September) took place only during years with abundance of water: 1993–1994, 1998 and 2002–2005.

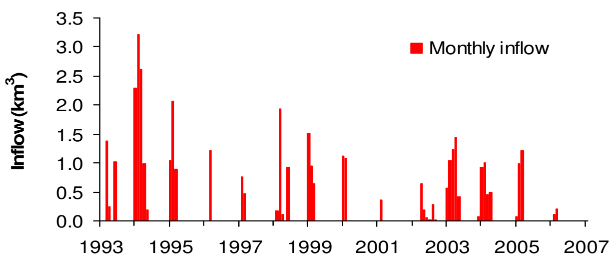

Fig. 2 The fluctuation of inflow from Chardara Reservoir during period from 1993 to 2006.

(2) Inflow from drainage network

The drainage network collects drain water from Golodnaya Steppe agriculture fields, mostly located in the eastern part of AALS. Within period of 1993-2006, it was ranging from 0.04 to 0.14 km^3/month (0.63–1.31 km^3/year). In average, it was about 0.86 km^3 or 21% from the total inflow of AALS and indicates that the drainage water significantly contributed to the AALS. Within last 13 years, there was about 12.09 km^3 of disposal flow from the collector–drainage waters (**Fig. 3**).

(3) Inflow from rainfall

The monthly rainfall pouring over the lake is calculated from the observed data of closest rainfall station (Mashikuduk Sta.). In period of 1993-2006, the rainfall varied about 0–87 mm/month (60–250 mm/year). By multiplying it with the lake area, their contribution as inflow into AALS was ranging 0.0–0.28 km^3/month (0.19–0.74 km^3/year). In average, the annual inflow was about 0.47 km^3 or 12% of the total inflow of AALS. It was about 6.45 km^3 of inflow from rainfall (**Fig.4**). Although the rainfall is not much high, its availability is an important factor for sustainability of the ecosystem surrounding the lake. It also helps to reduce the salinity caused by the high evaporation rate during summer season. Furthermore, the rainfall would be the single inflow if Kazakhstan is reducing the water into AALS in near future.

(4) Outflow from evaporation

The assessment of evaporation over lake was done by adopting the formula of Hydrometeoizdat, Leningrad 1969, the Russian old methodology derived from hydro-meteorological observations. Since it is a local method and practiced domestically then it is supposed to have a better representation of the actual conditions. That formula is expressed as follow (Appatiev)[14]:

$$E_0 = 0.14\, n\, (e_s - e_{200})\, (1 + 0.72\, U_{200}) \qquad (4)$$

where,

- E_0 = evaporation rate over the lake surface (mm/month),
- n = number of days,
- e_s = partial pressure of saturated water vapor at the lake surface (hPa),
- e_{200} = partial pressure of water vapor at 200 cm height above the lake surface (hPa),
- U_{200} = wind speed at the height of 200 cm (m/sec) above the lake surface.

The parameter of monthly surface water area is one of the important included parameter in this study rather than a fixed value (i.e. annually) as used by other researchers. So the dynamic of evaporation in AALS could be better represented here.

Evaporation plays major losses in AALS as typical losses in arid regions. Here the evaporation is higher than rainfall. The fluctuation of evaporation rate is shown in **Fig.5**. Analyzed from 13 years of historical data, at the peak of summer season, July, it was fluctuating between 170 to 265 mm/month. The average value was 220 mm/month. The annual evaporation rate was 2.9 km^3/year (950 mm/year). The highest portion of the evaporation losses was estimated on May to September (2.5 km^3/5 months, 84 % of the annual value).

(5) Outflow for irrigation

The irrigation period in this area is three months-based (June to August). The irrigation water is acquired by directly pumping out the lake water and distributed it through open canals to the agriculture fields. Their fluctuation of water abstraction for irrigation is shown in **Fig.6**. The water demand for irrigation is estimated to be 0.037 km^3 annually or 1 % of the total outflow.

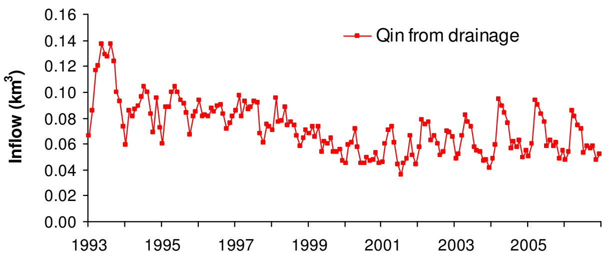

Fig.3 The dynamics of flow/discharge of collector–drainage water to AALS.

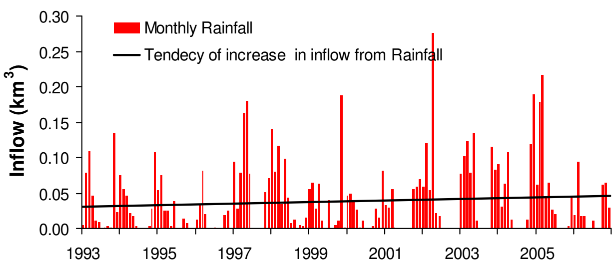

Fig. 4 The inflow from rainfall over AALS.

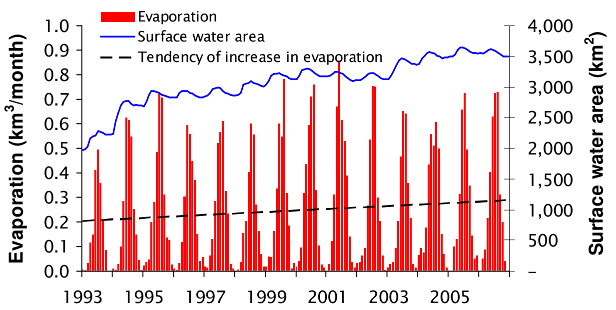

Fig.5 The monthly evaporation, tendency of increase in evaporation and surface water area in AALS.

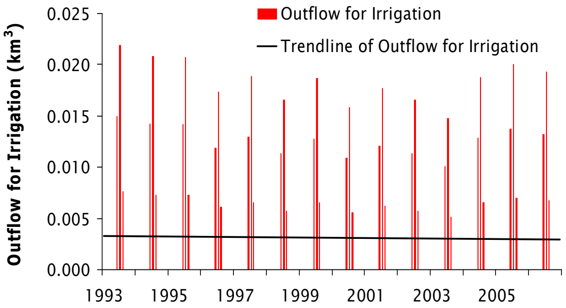

Fig.6 The fluctuation of water abstraction for irrigation.

(6) Water storage in AALS

The monthly fluctuation of volume of water storage in AALS (ΔV) is calculated by a regression formula that represents the relationship between topographical (*morphometric*) data and the observed water level (H) (see **Table 1**).

$$V = 0.0721H^2 - 32.107H + 3573.1 \qquad (5)$$

The differences of water level and water storage with previous month are defined as ΔH and ΔV respectively. The fluctuation of monthly value of ΔH and ΔV is shown in **Fig.7**.

Table 1. The relationship between water level and volume of AALS,

Elevation	Volume	Elevation	Volume	Elevation	Volume	Elevation	Volume
(mBS)	(km^3)	(mBS)	(km^3)	(mBS)	(km^3)	(mBS)	(km^3)
217.5	0.187	227.5	3.338	237.5	15.950	247.5	44.546
220.0	0.552	230.0	5.146	240.0	21.512	250.0	54.467
222.5	1.164	232.5	7.784	242.5	28.082	252.5	65.484
225.0	2.070	235.0	11.389	245.0	35.754	255.0	77.392

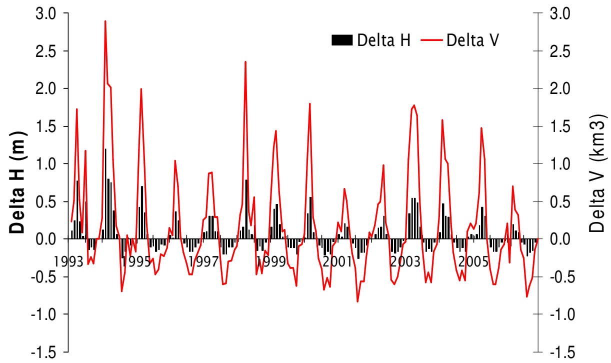

Fig.7 Fluctuation of water level and water storage in AALS.

The maximum ΔV was happened on February 1994, when extreme floods occurred in Syrdarya River delivered surcharge inflows to AALS. In 1994, the annual inflow was about 9.3 km^3. It was the highest inflow during the period of 1993-2006. The minimum remaining water was appeared on August 2001, with annual inflow of 0.351 km^3 as seen as the lowest inflow of 13 years observation data.

(7) Groundwater exchange

The summation of recharge and discharge of groundwater (flux) is known as groundwater exchange. Groundwater exchange (GWex) can be considered as positive when the flux is positive (flowing to the lake, lake is as a control volume) and as negative when the flux is negative (leaving from the lake).

The GW exchange in AALS is summarized in the **Table 2**. The annual average of GW exchange in AALS is about +0.7 km^3 with about +2.44 km^3 of GW recharge and about –1.74 km^3 of GW discharge. Within period of August to February, the GW exchange has negative value, thus being considered as discharge and may contribute to the decreasing of lake's water storage. The positive value happens during period March–July (**Fig.8**).

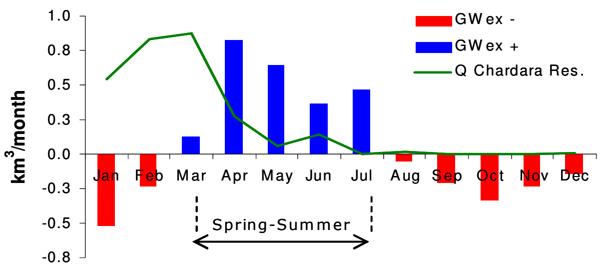

Fig.8 Groundwater exchange in AALS.

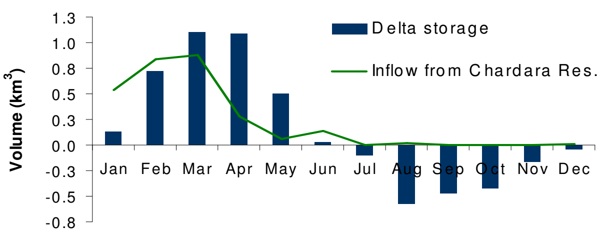

Fig.9 Monthly delta storage and inflow from Chardara Res.

Table 2. Monthly estimated of GWex in AALS (by Eq.3),

Water volume (km3)	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Inflow from Chardara reservoir	0.54	0.84	0.88	0.28	0.06	0.14	0.00	0.02	0.00	0.00	0.00	0.01	2.76
Inflow from drainage network	0.06	0.07	0.08	0.09	0.08	0.08	0.07	0.07	0.07	0.06	0.06	0.06	0.86
Rainfall	0.06	0.07	0.07	0.06	0.04	0.02	0.01	0.00	0.01	0.01	0.06	0.05	0.47
Total Inflow	0.66	0.98	1.03	0.43	0.18	0.24	0.08	0.10	0.08	0.08	0.12	0.12	4.09
Evaporation	0.01	0.02	0.06	0.17	0.33	0.57	0.63	0.61	0.33	0.15	0.05	0.02	2.94
Irrigation	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.00	0.00	0.00	0.00	0.04
Total outflow	0.01	0.02	0.06	0.17	0.33	0.58	0.65	0.62	0.33	0.15	0.05	0.02	2.98
I-O	0.64	0.96	0.97	0.26	-0.15	-0.34	-0.57	-0.52	-0.24	-0.07	0.08	0.10	1.12
GW exchange	-0.51	-0.24	0.13	0.83	0.64	0.37	0.47	-0.05	-0.22	-0.34	-0.23	-0.14	0.70
Delta storage	0.13	0.72	1.10	1.09	0.50	0.03	-0.10	-0.57	-0.47	-0.42	-0.16	-0.04	1.82

The lowest level of water deficit in AALS was observed on August (–0.57 km^3, approximately 32 % of the total amount of water deficit during 6 months). The period of January–June, the water storage becomes surplus (**Fig.9**). Even though June is a month in the summer season but the rate of evaporation could be balanced by the inflow from upstream and groundwater exchange which plays as recharge to the lake. The maximum value of surplus water has been recorded on March (1.1 km^3, approximately 31 % of the total amount of surplus water within 6 months).

(8) Groundwater exchange processes

Lakes interact with groundwater by receiving groundwater inflow through part of their bed and have seepage loss through other parts. According to the geological setting of AALS (**Fig.10**), the GW flows mainly initiate from southern boundary/ mountain area enter to AALS as recharge. Also, there is GW discharge as lake seepages flow towards the plain area in the northern part (Kyzylkum Desert, the right side in **Fig.10**). The schematic water balance and the interaction of groundwater and AALS is roughly plotted in **Fig.11**.

Qualitatively, the GW exchange has positive contribution to the increasing of the lake water level. Consequently, a negative GW exchange may affect the decrease of the lake water level. Within 77% probability of occurrence, when delta lake water level (ΔH) is positive then GW exchange also tends to be positive. So, when delta lake water storage (ΔS) is positive then at the same time GW exchange tends to be positive also, and vice versa (**Fig.12**). Anomalies happen when the ΔS was nearly zero at several months (i.e. beginning 1994, 1995, 1998, 1999, 2000 and 2005). Here, the amount of inflow was nearly equal to the evaporation losses. Here, the sounds of ΔS, ΔH and GW exchange interaction are essential to understand the hydrologic quantity.

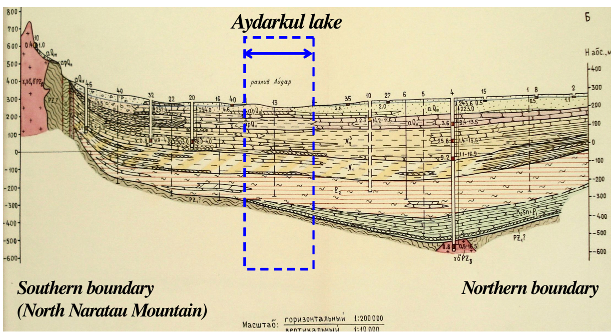

Fig.10 Main geological setting of transversal cross section of Aydarkul Lake, south to north-wise *(adapted from Research Institute of Hydro-Meteorology, Uzbekistan).*

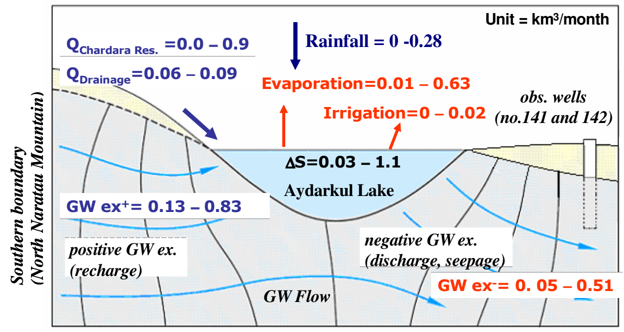

Fig.11 Schematic of water balance and GW exchange processes in AALS.

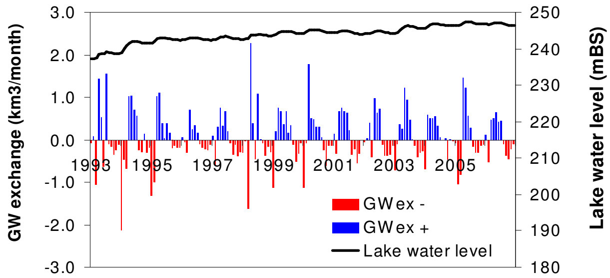

Fig.12 Lake water level and groundwater exchange in AALS.

Table 3. GW re/discharge in AALS and Dulce Lake,

	AALS	Dulce Lake
GW recharge	700	440
GW discharge	500	630

Unit mm/year

As a comparison, a similar study by water budget approach in other semi arid area, Dulce Lake at Southern Spain, is given in **Table 3** (Rodriquez *et al.*)[15]. In Dulce Lake, the potential GW recharge is lower than GW discharge. In contrast to Dulce Lake, in AALS the potential GW recharge is higher than GW discharge and it tends to maintain the lake water level increase.

(9) Verification

The GW discharge (seepage) out from the lake body leads to the increasing of GW level monitored in the wells at northern area (**Fig.13** and **Fig.14**).

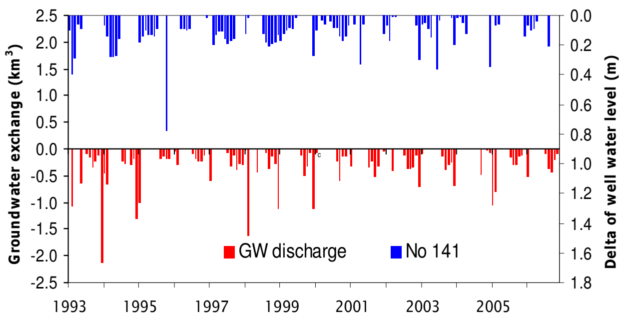

Fig.13 Groundwater level in well no. 141 and negative groundwater exchange (GW discharge).

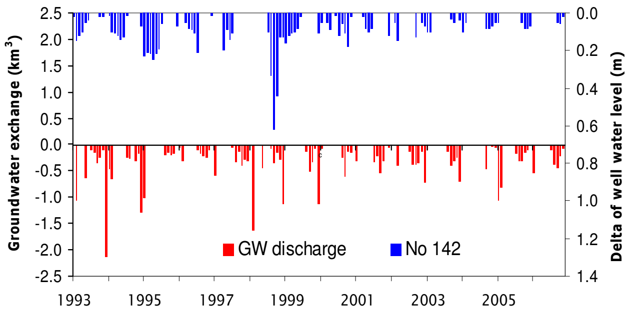

Fig.14 Groundwater level in well no. 142 and negative groundwater exchange (GW discharge).

Following the Darcy Law and by incorporating the characteristic of soil nearby lakes as well as nearest distance between the lake and the wells, then the time lag between the GW discharge and increasing water table is about 1-2 months. It all agrees with and supports to the result of LWB approach.

5. CONCLUSION

The groundwater exchange between AALS and surrounding aquifers has been successfully assessed by a unique LWB trimmed for semi arid/arid area. Here LWB was selected, because the lake is the only measurable important element of water balance in arid/semi arid area. It is a monthly-based LWB by introducing the lake surface area as function of observed lake water level. The proposed LWB was able to quantify the amount of groundwater recharge (into the lake) and discharge (out from the lake).

From March to July, GW recharge is higher than GW discharge as indicated by positive GW-exchange ranging from 0.13 to 0.83 km^3/month. In the period from August to February, GW discharge is higher than GW recharge (a negative GW-exchange). It's about -0.05 to -0.51 km^3/month.

Verified with the observed data, this approach seems successfully to serve as a reliable method for the reconstruction of GW-exchange into/out from the lake (AALS). It may bring useful information for the policy makers in Kazakhstan and Uzbekistan lead to successful formulation and implementation of transboundary water management plans.

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