CHAPTER 3: GROUNDWATER RESOURCES IN THE ARAL SEA BASIN

Authors: Abror Gafurov[1], Vadim Yapiyev[2], Mohamed Ahmed[3], Jay Sagin[2], Ali Torabi Haghighi[4], Ermek Murtazin[5], Aigul Akylbekova[5], Bjørn Kløve[4]

[1]GFZ German Research Centre for Geosciences, Section: Hydrology

[2]Department of Civil and Environmental Engineering, School of Engineering, Nazarbaev University, Astana, Kazakhstan

[3]Department of Physical and Environmental Sciences, Texas A&M University – Corpus Christi, USA

[4]Water, Energy and Environmental Engineering Research Unit, Oulu University, Finland

[5]Institute of Hydrogeology and Geoecology named after Akhmatsafin, Almaty, Kazakhstan

KEY MESSAGES

Groundwater is a main water resource providing a stable supply for different users. Groundwater resources has to be managed as a none-renewable resources to keep a balance between recharge and demand (pumping) to avoid groundwater depletion. Aquifers can be on local, regional and transboundary scale that often needs to be managed as a common pool. As surface waters are often linked to aquifers they should be managed jointly (conjunctive use). The key messages for the Aral Sea basin (ASB) groundwater are:

1. In ASB, groundwater is used for rural water supply, irrigation and as a supply for some major cities.
2. Recently groundwater use has been increasing due to developing agriculture. Exploitation of aquifers is favored by lower infrastructures investments typical to surface water use.
3. The proportion of groundwater use varies between countries. Tajikistan and Afghanistan use 19.7 % and 15% respectively, while the Turkmenistan uses only 1.1% of groundwater of the total withdrawal.
4. The water balance of the Aral Sea shows that the role of groundwater has increased drastically from 1960 to 1996, beeing 12 % of the all river runoff in 1960 to approximately 100% in 1996.
5. In many region, the seasonal variation of groundwater levels is linked to water consumption during irrigation season. Higher groundwater levels due to irrigation is a risk for soil salinity. Reduced groundwater levels is a serious threat to ecosystems and increases desertification.
6. The role of changed land use and climate change on recharge needs more studies. Groundwater recharge seems to reduce due to reduced soil moisture in the ASB, which could be due to increased evaporation.
7. In lack of in-situ data on groundwater, the total water balance storage (TWS) variation is estimated by remote sensing (GRACE). This indicates that ASB is experiencing a TWS depletion of -3.35 ± 0.45 mm/year.
8. Groundwater quality is deteriorated in many parts where intensive irrigation for agricultural takes place. This is because drainage systems are no longer maintained leading to salt deposition in the soil.

INTRODUCTION

Groundwater in the Aral Sea Basin (ASB) has a special role as a large water storage, which interacts with the surface water systems. Major rivers originating in the mountains are mainly fed by groundwater during winter when precipitation falls and it stored in the snowpack leading to little runoff. In summer months, melting snow and river discharge recharge groundwaters in the region. Despite the importance of groundwater, the observations and quantification methods in the ASB are not developed as for surface water. For integrated and sustainable water management the surface and groundwater resources should be considered jointly.

In the ASB, groundwater resources are important for agricultural production and for drinking purposes. Moreover, groundwater act as a buffer for environmental flow during drought years with limited availability of surface water resources (Zhiltsov et al., 2018). With the population increase and potential decrease of natural water availability from the rivers due to climate change, the pressure on groundwater resources is most likely to increase. This may lead to groundwater depletion and degradation of groundwater quality, and after 1960's the groundwater status has deteriorated. Understanding the processes related to groundwater resources is essential to ensure food security in the region.

This chapter, first, gives an overview about groundwater demand and supply in the region followed by analysis of inter-annual groundwater variation and trends of groundwater levels using observed and gravimetry-based time series, respectively. Moreover, quality of groundwater in the region is also highlighted. The relevance of groundwater resources to socio-economy of Central Asian region is then discussed and challenges in managing groundwater resources in the future are described.

GROUNDWATER SUPPLY AND DEMAND

The land cover in the ASB include high mountainous areas in the southeast with high precipitation were water is formed from glacier and snowmelt from the mountains of Pamir and Tian-Shan. The very flat lowlands in the course of Amudarya and Syrdarya rivers has well established agricultural production, where water is consumed for irrigation (Figure 1). The amount of rainfall in lowlands is less than 200 mm year^{-1} and the actual evapotranspiration in the lowlands may well exceed 700 mm from April-October only (Forkutsa, 2009a). As in arid regions, in a pristine state without irrigation, groundwater recharge would occur mainly through rivers and ephemeral stream as focused recharge often during episodic events (Cuthbert et al. 2016). Recently, Micklin (2016) estimated renewable usable groundwater resources in the Aral Sea basin to be as high as 44 km^3, of which 16 km^3 is freshwater that may be connected to surface water resources and managed carefully. Micklin (2016) state the loss of important ecosystems and increasing desertification due to surface water and groundwater depletion.

Irrigation of the lowlands in the ASB leads to groundwater recharge of lowlands due to irrigation in the summer months. Moreover, winter runoff also became an important source of shallow groundwater recharge and river bank infiltration. This is due to the modified reservoir operation in upstream countries where large amount of water is released during winter months when energy production is at its maximum. This change has influenced the intra-annual hydrological regimes.

In ASB, groundwater is often the main source for domestic water supply in rural areas and in a major resource in some cities (Rakhmatullaev et al., 2010, UNESCO-IHP, 2016). It has been previously assumed that the fresh groundwater resources in the deserts of Central Asia are rather large and satisfy, in some areas, the demands for crop irrigation (Ostrovsky, 2007). Since the Soviet times, the groundwater was considered to represent a strategic resource, but surface water (such as rivers, canals, lakes and reservoirs) were primarily sources of water supply. The groundwater exploitation in the ASB has, however, been increasing in recent years due to its good quality and quantity and as an alternative to the surface water. In the ASB, extensive use of groundwater for irrigation purposes began in the drought years of 1998-2001 to sustain agricultural production (FAO, 2013). Since then, groundwater is considered to be a reliable source of water for agricultural production.

Among countries sharing ASB, Afganistan has the most share of groundwater use (15 %) for irrigation and drinking purposes to meet countries demands for water resources (Table 1). Excessive use of groundwater for irrigation purposes has significantly depleted aquifers in Afghanistan, which may lead to severe shortage of drinking water (FAO, 2013). Groundwater is extracted throughout the country to meet demand for irrigation and drinking water (Figure 2).

Groundwater extraction is highest in Uzbekistan with about 5 km^3 (5.000 million m^3) (8.9 % of total water consumption) among countries sharing ASB boundary, followed by Afghanistan, which has an extraction rate of about 3 km^3 (15 % of total water consumption) (Table 1). Turkmenistan and Kyrgyzstan are among lowest groundwater extractors with about 0.3 km^3 each (3.8 % Kyrgyzstan, 1.1. % Turkmenistan). Despite similar geographic condition of Tadjikistan with that of Kyrgyzstan, the groundwater extraction rate in Tadjikistan with about 2.3 km^3 (19.7 % of total water consumption) which is much higher than in Kyrgyzstan. Kazakhstan's groundwater extraction rate is about 1 km^3 (4.9 % of total water consumption) (FAO, 2013).

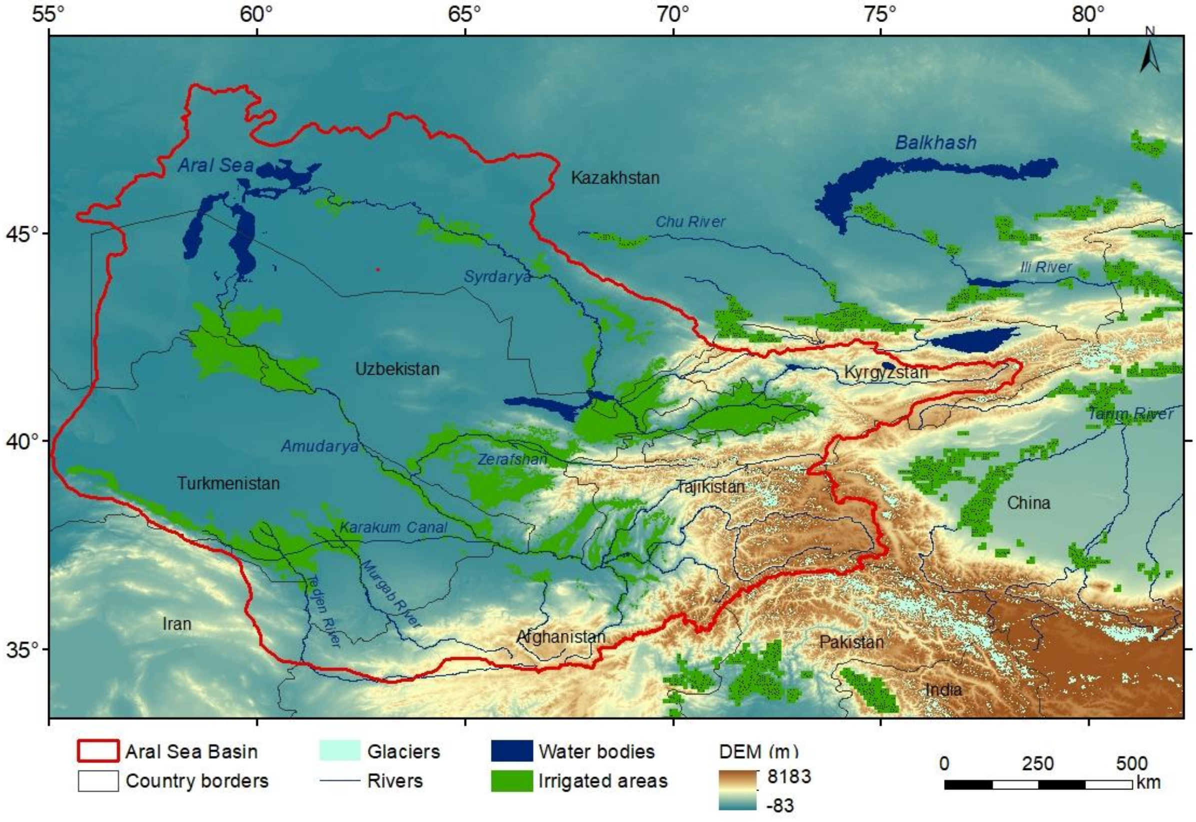

Figure 1. Irrigated areas in Central Asia (green color after Conrad et al. 2016; green color with black dots after FAO 2016).

Table 1. Share of surface and groundwater used for irrigation in Central Asia (Source: FAO, 2013).

Country	Annual water withdrawal (km³)					Area irrigated using (thousand ha)			
	Total	Surface water	%	Ground-water	%	Surface water	%	Ground-water	%
Afghanistan	20.4	17.3	85.0	3.1	15.0	2631	82.0	577.2	18.0
Kyrgyzstan	8.0	7.4	92.4	0.3	3.8	1011	99.0	10.2	1.0
Tadjikistan	11.5	8.9	77.7	2.3	19.7	696	93.9	32.5	4.4
Uzbekistan	56.0	44.2	78.9	5.0	8.9	3929	93.6	268.7	6.4
Turkmenistan	27.9	27.2	97.4	0.3	1.1	1981	99.5	9.6	0.5
Kazakhstan	21.1	18.9	89.7	1.0	4.9	1197	99.8	2.0	0.2

In some parts of the ASB, the trends of irrigated areas with groundwater withdrawal varied from country to country in the past. For example, in Afghanistan the irrigated areas with groundwater withdrawal increased from 492.646 ha in 1993 to 577.156 ha in 2002. This rate decreased in Tadjikistan from 68.000 ha in 1994 to 32.500 in 2009 (FAO, 2013).

As shown in Table 1, Tadjikistan has the highest share for groundwater use (19.7 %) followed by Afghanistan (15 %) and Uzbekistan (8.9 %). Kyrgyzstan (3.8 %) and Turkmenistan (1.1 %) had least groundwater withdrawal to meet demand. In Kazakhstan this is about 4.9 %. However, Kazakhstan has limited share of ASB and thus of less relevant to this study.

Groundwater resources are extremely important for Afghanistan since about 18 % of agricultural area in the country is irrigated by groundwater withdrawal, which can also be justified with the intensity of groundwater extraction illustrated in Figure 2. Uzbekistan with its about 6.4 % agricultural area being irrigated by groundwater withdrawals is the second major consumer of groundwater resources in the ASB, followed by Tadjikistan (6.4 %). Kyrgyzstan, Kazakhstan and Turkmenistan use groundwater on for less than 1 % of the irrigated area.

Extensive groundwater use can decrease surface water availability. In Uzbekistan, the threshold for actual groundwater withdrawal with no impact on surface water is estimated to 7.5 km/year. For whole Aral Sea basin, the groundwater potential for extraction are estimated to be 13.1 km³/ year (CAWater-Info, 2011).

REGIONAL AND TRANSBOUNDARY AQUIFERS

The regional groundwater reserves in the ASB is estimated to be about 31.17 km³, of which 14.7 km³ is located in the Amudarya basin and 16.4 km³ are located in the Syrdarya basin. About 30 % of these reserves are of transboundary nature (CAWater-Info, 2018). Groundwater recharge happens by rainfall and river flow originating from mountains of Pamir and Tianshan. In the last years, researchers focused on identifying large aquifers in the territory of Central Asia (Lee et al., 2018, Karimov et al., 2014). In addition, international partners have carried out groundwater mapping in some regions. Large aquifers can be used as potential water storage and sources (Karimov, et al. 2014).

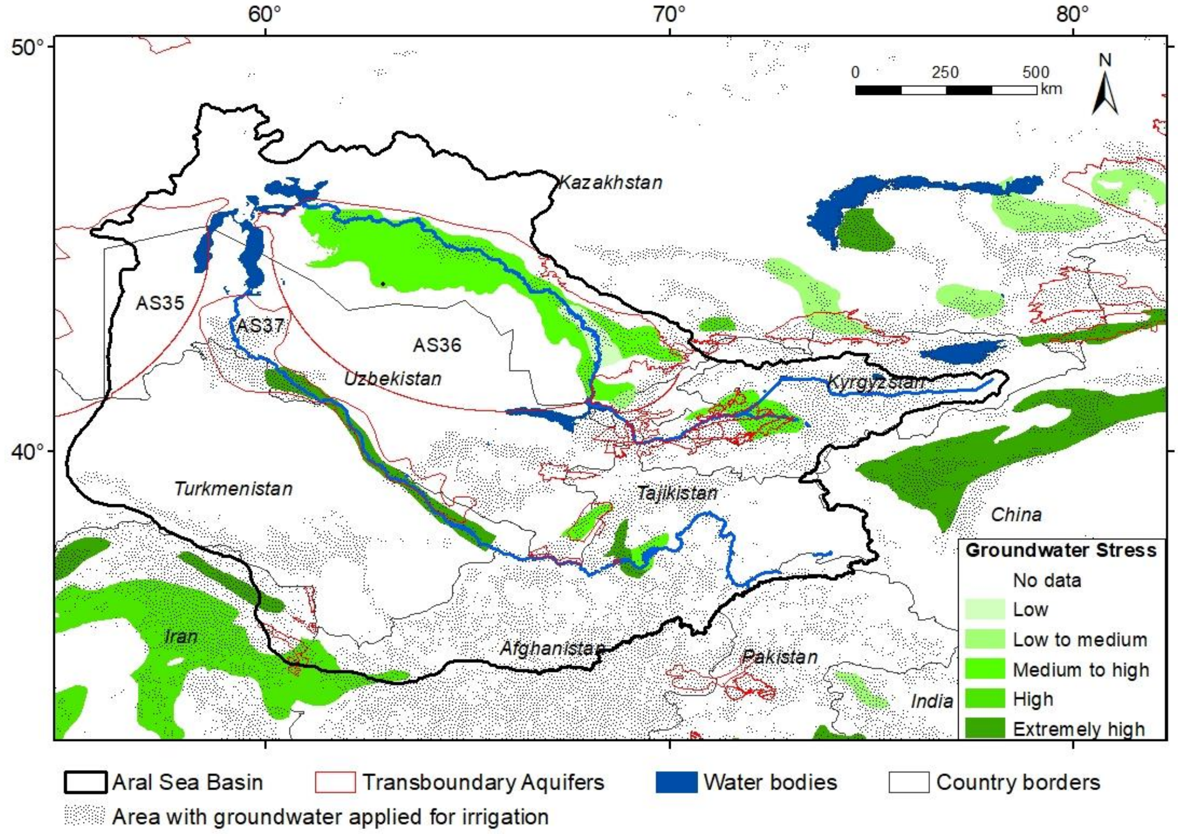

Figure 2. Map of the Aral Sea Basin with Transboundary Aquifers (TBAs), areas with groundwater applied for irrigation and groundwater stress index. The largest TBAs with international codes of AS35, AS36 and AS37 are located in the Amudarya, Syrdarya and Birata-Urgench artesian basins (Source: UNESCO-IHP-WINS)

The largest aquifer in the region, with an area of about 400,000 km², is the Syrdarya Aquifer (Figure 2) located between Kazakhstan and Uzbekistan (Lee et al. (2018). The second largest transboundary aquifer in the ASB is the Amudarya artesian basin. It is located between Kazakhstan, Turkmenistan and Uzbekistan and covers the area of about 260.000 km². The third largest transboundary aquifer system in the ASB is the Birata-Urgench artesian basin located along the Amudarya River. The Birata-Urgench artesian system covers about 80.000 km² of area and is located between Turkmenistan, Uzbekistan and Kazakhstan. All of these aquifer systems are connected to the Aral Sea, the Syrdarya artesian system being connected to the southern-east part of the Aral Sea, the Amudarya artesian system being connected to the northern part of the Aral Sea and the Birata-Urgench artesian system being covered to the southern part (Amudarya Delta) of the Aral Sea. The aquifers with the connection to the Aral Sea also contributes to the water balance of the lake. Jarsjö & Destouni (2004) estimated total groundwater contribution to water balance of the Aral Sea after 1960 to 1996. They concluded that the role of groundwater had been increased drastically during this period from 12 % of the all river runoff in 1960 to approximately 100% in 1996 due to well-known streamflow reductions from the Amudarya and Syrdarya rivers. Oberhänsli et al. (2009) performed extensive stable water isotope (hydrogen and oxygen) survey (2004-2006) and characterization of the Aral Sea water. One of their goals was to assess the interactions between the Aral Lake and groundwater based on several locations. They concluded that groundwater flow contribution to the Aral Sea is significant in the spring and the autumn. The stable water isotopic composition of both artesian, shallow groundwater and the lake indicates the increased importance of fossil (old) subsurface water flow input, most probably due to lowering of the water level of the Aral Sea over the years.

During the Soviet time, the aquifers were studied with regards to their potential for water supply in the region. For example, a study was conducted to analyze aquifer potential for water supply of the Pretashkentskiy Aquifer and limits for groundwater extraction was set. These were 1464 m³/day for Kazakhstan and 2044 m³/day for Uzbekistan for the Pretashkentskiy transboundary aquifer, which is located between Kazakhstan and Uzbekistan. The total groundwater volume of this TBA has been estimated to be as high as 97.6 km³ (UNESCO, 2016).

Figure 2 also shows areas with groundwater used for irrigation. Groundwater extraction for irrigation mainly occurs along the rivers of Central Asia. Moreover, an intensified groundwater use for irrigation can be observed at the Amudarya Delta. Figure 2 also shows groundwater stress index, which shows areas where groundwater extraction is much higher than groundwater recharge. According to Figure 2, the groundwater stress along the Amudarya River is extremely high and along the Syrdarya River it is moderate to high.

SEASONAL VARIATION OF GROUNDWATER IN AMUDARYA IRRIGATED LOWLANDS

In the Amudarya River delta, about 1200 mm surface water is used seasonally for cotton production alone (Conrad, 2006), of which about 430 mm of water is for pre-season soil leaching (Djanibekov, 2008), which is essential in many parts of Central Asia to cope with salinity (Ibrakhimov, 2007). Also water losses to groundwater occur from unlined irrigation canals (Forkutsa, 2009 a). Due to irrigation, the seasonal groundwater level fluctuation is over 100 cm in places (Schettler, et al 2013). In the Khorezm region (Amudarya delta), the groundwater level rises in spring with the start of cropping activities (pre-season leaching) with a peak in March-April (Figure 3). A second peak is observed in July-

August, when the irrigation is at its maximum. The groundwater levels are the lowest during winter (Ibrakhimov, 2004).

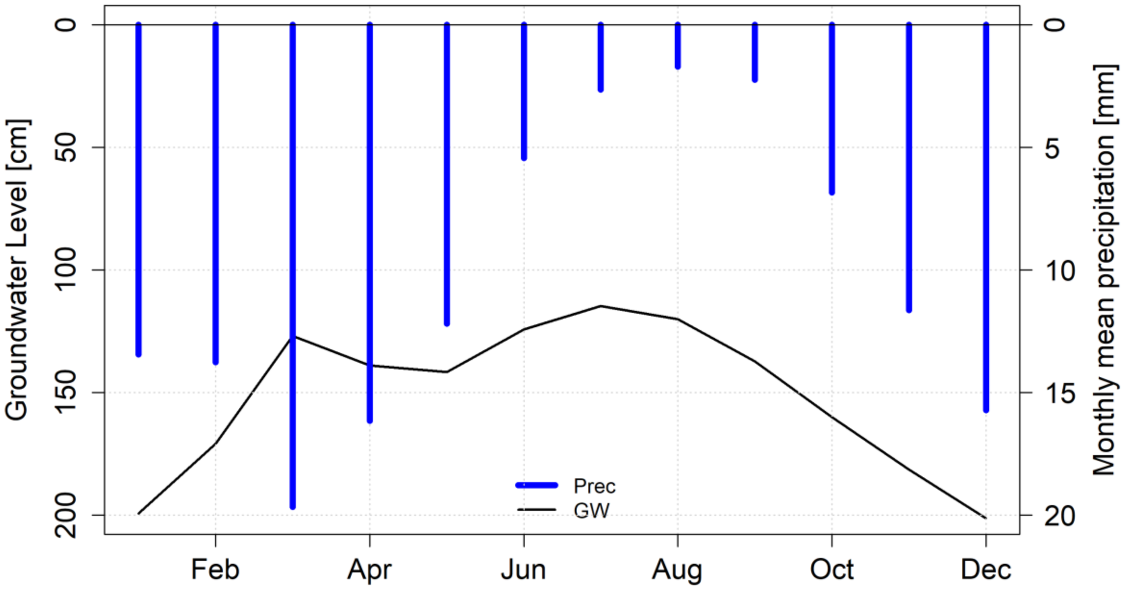

Figure 3. Seasonal variations of groundwater table in the Amudarya Delta. Monthly values correspond to long-term means derived from decadal observations during the period from 2000 to 2005 in the Khorezm region. The precipitation data is the long-term means derived from daily precipitation observations at Urgench meteorological station in the period from 1936 to 2006.

GROUNDWATER VARIABILITY OBSERVED BY GRACE SATELLITE DATA

As data availability on groundwater observations in Central Asia is limited, the remote sensing-based observation was used to reveal the spatial variations of groundwater in the region. As an integrated dataset of total water storage (TWS) variations, representing the total, vertically integrated, variations of water stored as ice, snow, soil moisture, groundwater and surface water bodies, we use the Gravity Recovery and Climate Experiment (GRACE) data. GRACE is a joint satellite mission between National Aeronautics and Space Administration (NASA; USA) and German Aerospace Center (DLR; Germany) launched in March 2002 to map the global, temporal and static, gravity fields of the Earth (Tapley et al. 2004). GRACE data have been successfully applied to monitor groundwater resources in several parts of the world (e.g., Ahmed et al., 2014, 2014, 2016; Sultan et al. 2013, 2015a; Mohamed et al. 2016; Fallatah et al. 2017, 2018; Ahmed and Abdelmohsen 2018; Niyazi et al., 2018) including Central Asian region region (Ebead et al., 2017; Deng and Chen, 2016, Xie et al., 2018, Chao et al., 2018).

As the other components of TWS (e.g. surface water, snow and ice) are negligible in the lowland areas of Central Asia, we attribute the spatiotemporal variations in TWS data, obtained by GRACE satellites, mainly to spatiotemporal variations in soil moisture and groundwater storages. Monthly GRACE mass concentration (mascon) solutions, generated by the University of Texas Center for Space Research (UTCSR), spanning the period from April 2002 to June 2017 is used in this study. GRACE masons solutions do not require spectral (e.g., destriping) and spatial (e.g., smoothing) filtering and provide higher signal-to-noise ratio, higher spatial resolution, and reduced error compared to other GRACE solutions (e.g., Save et al., 2016). UTCSR mascons solutions are used GRACE data only to constrain the gravity field solutions over hexagonal grids (1° at the Equator, total 41,000) that have been resampled at 0.5° x 0.5° TWS grids. TWS time series over investigated areas are generated by spatially averaging all TWS results over the spatial domain of that area. Trends in TWS data are extracted by simultaneously fitting annual (sine and cosine), semiannual (sine and cosine), and a trend parameter to each TWS time series. The TWS trend solutions over Central Asia are shown in Figure 4.

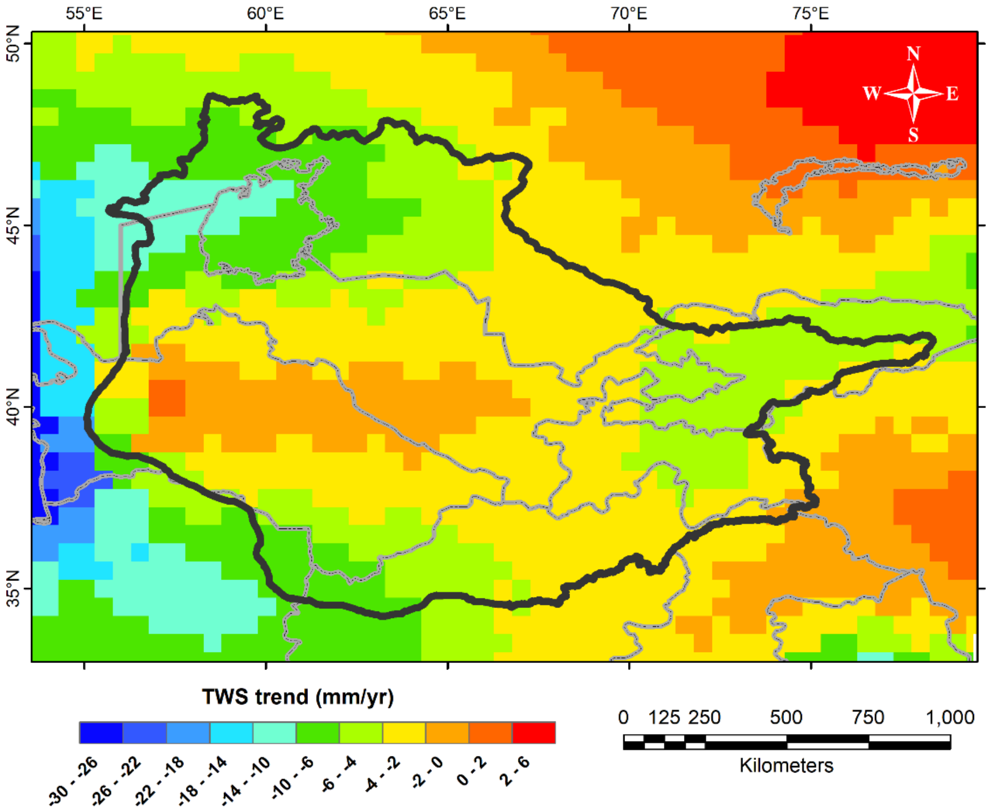

Figure 4. Secular trends (mm/yr) in GRACE-derived TWS over the Central Asia region and surroundings. Also shown is the spatial distribution of the ASB (black polygon).

Blue areas (negative TWS trends) on Figure 4 are witnessing TWS depletion trends, whereas, red areas (positive TWS trends) are experiencing TWS wetting trends. Inspection of Figure 4 indicates that areas to the northeast and southwest of the ASB are witnessing wetting TWS trends, whereas, areas west of the ASB are witnessing TWS depletion trends. Within the ASB, TWS trends are getting more depleted away from the center of the ASB. Given the fact that GRACE data have no vertical resolution, independent sources for soil moisture, reservoirs, and snow/ice storage should be utilized to quantify the GRACE-based groundwater storage. However, in this investigation the TWS was used as a proxy for the "Accessible Water" storage given the scale of the study area. Accessible water storage variations are defined, in this study, as changes in the combination of groundwater, soil moisture, surface water, and snow/ice.

Figure 5 shows the temporal variations in GRACE-derived TWS over averaged over the ASB. Examination of Figure 5 indicate that the ASB is experiencing a TWS depletion of -3.35 ± 0.45 mm/year, which is equivalent to -5.82 ± 0.87 Gt/year. It is worth mentioning that TWS depletion rates during the period from 4/2002 to 3/2016 was estimated at -4.46 ± 0.52 mm/year (-7.75 ± 0.90 Gt/year) and these rates are quite similar to those (-7.31 ± 1.68 Gt/year) reported by Wang et al, 2018 during the same period. Surface water storage depletions is accounting for more than 80% of the observed TWS depletions in the ASB (Wang et al, 2018).The decline in surface water storage is attributed to a decline in rainfall rates and/or increase in evapotranspiration rates. The northern part of the ASB is witnessing increased evaporation rates. Figure 5 also shows an evaporation time series for Shalkar pan evaporation observation station. The increasing trends in pan evaporation indicate an increase in atmospheric demand for water and soil moisture dissication trend in the ASB. The sharp increase in evaporation rates over the ASB provides potential explanation for TWS decline. TWS decline over the ASB could be also attributed to groundwater extraction. The central parts of the ASB are lowland areas and are witnessing an increased groundwater extraction for agricultural activities and productions.

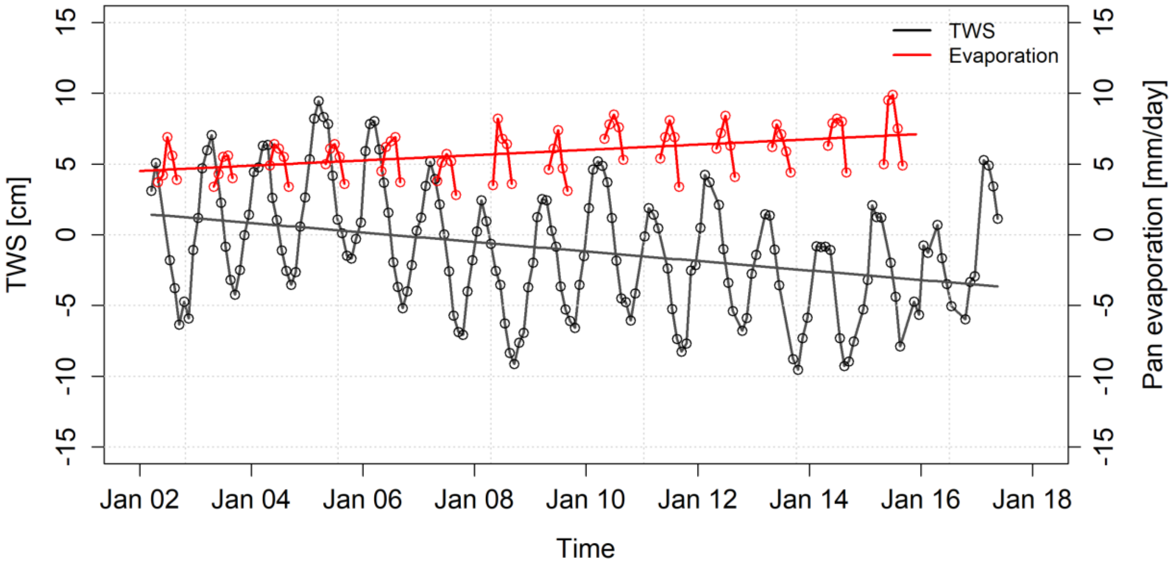

Figure 5: Temporal variations in monthly (4/2002 – 6/2017) GRACE-derived TWS (averaged over the ASB) and observed mean daily pan evaporation from May to September (5/2002 – 9/2015) at Shalkar observation point.

GROUNDWATER QUALITY

Groundwater quality in the ASB is commonly affected by agriculture, municipal wastewater as well as industry (Bekturganov et al., 2016). The quality of groundwater varies from region to region. In the areas close to mountains in the western part, the quality of groundwater is better compared to deltas of the Amudarya and Syrdarya, where a lot of return flow from irrigated areas decreases the groundwater quality (Abuduwaili et al. 2019).

The total dissolved content (TDS) depends on the aquifer and varies considerably in the ASB. The salt content of groundwater varies from 1 to 3 g/L (CAWater-Info, 2018). The shallow groundwater is more saline in the lowlands where intensive evaporation leads to salt accumulation in the top soil. For example in south-eastern part, in the Syrdarya River basin near Karatau ridge, groundwater (aquifer of Upper-Turon-Senonian deposits) is fresh (0.3-0.4 g/L) with dominance of bicarbonate and calcium ions (Panichkin et al., 2011). The groundwater salinity increases in aquifers from south to north and east to west directions in ASB with domination of chloride-sulfate ions. It is highest near the Aral Sea bed reaching as high as 50-100 g/L (Panichkin et al., 2011). Recently, Kazhydromet reported that in lowlands of Syrdarya River (Kyzylorda town) open water has salinity ranging from 1.0 to 1.3 g/L with sulphates content of approximately 500 mg/L. At the same time, decentralized groundwater potable water sources has overall acceptable salinity with sulphates level as for the surface water bodies (Ministry of Energy, 2017).

In areas with extensive irrigation, waterlogging causes contamination of groundwater drinking water sources from chemicals used in agriculture (World Bank, 2003). While shallow groundwater sources in this region had consistently high (exceeding maximum permissible limit) levels of water color index, turbidity, magnesium concentration, the samples from artesian water showed only elevated water color index. Shallow and fossil groundwater has good potential to satisfy the needs of local population in upper and lower reaches in ASB if the adequate water treatment technologies are implemented. Previously, Friedrich (2009) reported that ASB was contaminated by uranium in the Syrdarya River watershed from mining activities with groundwater also affected. Panikhin et al. 2011 reported, that, near the Aral Sea local population increasingly rely on groundwater as a main potable water source due to degradation of the water quality of the Syrdariya River. The contamination of shallow groundwater is of particular concern in the irrigated areas. The contaminants such as nitrates, ammonium and persistent organics migrate to groundwater used for drinking purposes (Panichkin et al., 2011). The proper surface and subsurface quality monitoring and mapping is needed in lowland areas of endorheic ASB in particular as these are the final sinks for contaminants.

GROUNDWATER MAPPING AND DATA AVAILABILITY IN THE ASB

The groundwater mapping and data sharing are outdated in the ASB. The publicly available geotabases are still missing hydrogeological maps. Most maps were developed during Soviet time and some countries do not have updated maps (Figure 6). Among Central Asian countries, Kazakhstan was renewing hydrogeological maps intensively in the past time.

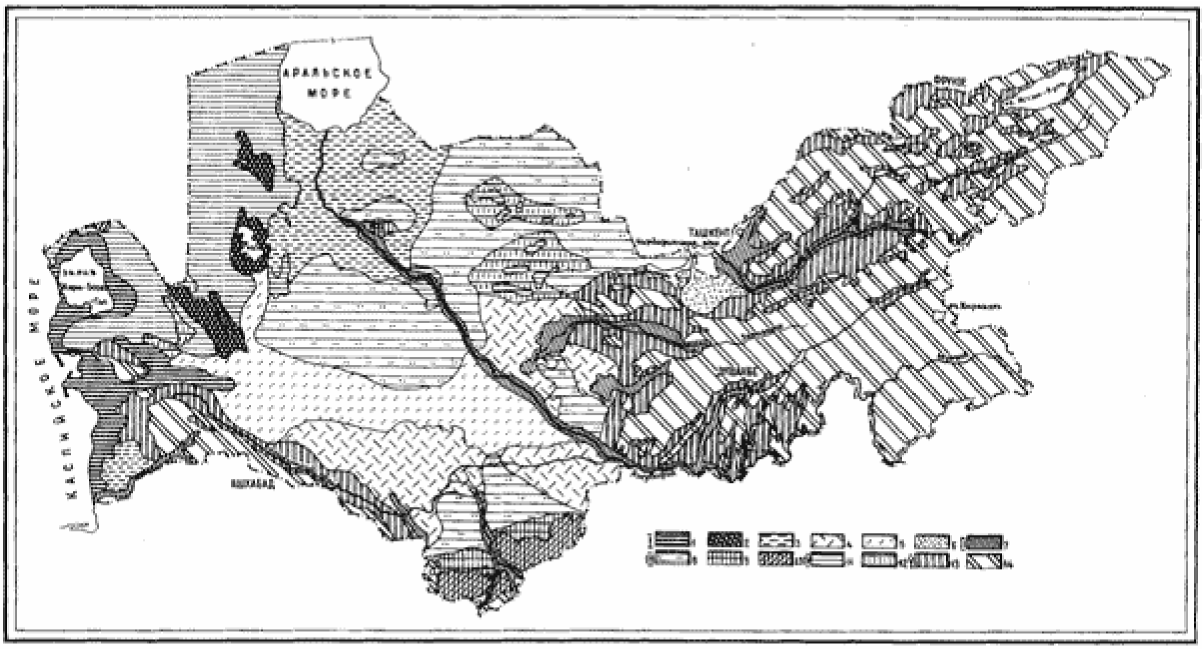

Figure 6. Hydrogeological map of Central Asia (Soyuzvodproekt, 1990).

Moreover, until now, some Central Asian countries still have data sharing restrictions, including information and mapping related to the groundwater resources. The International Groundwater Resource Assessment Center (IGRAC) has tried to conduct studies related to groundwater in the Trans-boundary Kazakhstan-Uzbekistan Pretaskent Aquifer and could manage to get access and study only part of Kazakhstan. There were restrictions to access the groundwater data, maps, hydrogeological studies from the previous Government of Uzbekistan. Only in the last year, the Uzbek scientists joined their Kazakh colleagues in common effort to assess and model groundwater resources of the Pretashkent Aquifer, during the expert meeting in Tashkent, held in May 2018 (UN-IGRAC, 2018). Currently mostly Syradarya river sub basin aquifers, hydrogeological information and mapping from Kazakhstan side are publicly available. The Amyrdarya river sub basin aquifer, hydrogeological information and mapping from Uzbekistan side are still having difficulties for publicity. However, there are dramatic changes in the region and more regional and international cooperation in joint research and data transparency is prioritized by the new Uzbek government.

SOCIO-ECONOMIC IMPLICATIONS OF GROUNDWATER USE

Groundwater use can directly influence river flow regime by decreasing the baseflow of rivers and drying springs and wells in headwaters. Change in surface water, could lead to failing the performance of current hydraulics, which are under operation. In addition, mining groundwater would be affected on groundwater-dependent ecosystem (Kløve et al., 2014) such as groundwater lakes that are found also in CA.

Elevated groundwater levels in regions with malfunctioning drainage system may lead to unemployment issues due to deterioration of soil quality (salinity) for proper agricultural production. About 70 % of irrigated land in downstream Amudarya areas has groundwater level of about 1.5 meters (NATO, 2006). This may lead to severe land degradation in the ASB.

In the ASB, the groundwater resources are becoming more important as an alternative source of water for irrigation and drinking, due to the frequent droughts in the last years (1998-2001, 2007-2008, 2018). In many parts of Central Asia, depletion of groundwater in these years were significant with decreased amount of water to be pumped below the ground due to insufficient groundwater recharge. Thus, groundwater highly contributes to food security and economic stability in the ASB.

Use of fertilizers and pesticides for agricultural production in Central Asia can contribute to reduced groundwater quality of aquifers. A recent assessment state that CA governments have adopted a more environment friendly production strategy (Berkum 2019). Salty and arsenic groundwater is a characteristic of the region. Information on pollution such as pesticides or nitrates concentrations are lacking.

In places, groundwater is also used as mineral water (fresh groundwater) filled in bottles and sold as fresh drinking water. For example in the Pretashkenstkiy TBA, 0.265 km^3 of fresh groundwater was used for bottling and as drinking purposes (UNESCO, 2016).

FUTURE CHALLENGES IN GROUNDWATER USE

Artificially recharged groundwater storage-water banking could be considered as one of the options to meet water security in the future in the ASB (Karimov, et al. 2014). However, thorough research studies must be conducted to understand groundwater storage potential in the region. The managed aquifer systems are superior in terms of evaporation losses compared to surface reservoirs, which also have a function of water storage for drought. However, increased water storage might lead to increased use of water and expansion of agricultural lands which might lead to water scarcity.

Elevated groundwater level due to insufficient irrigation approaches (e.g. surface irrigation) and malfunctioning drainage system (Dukhovny et al., 2017) may further lead to deterioration of groundwater quality and salinization of agricultural land. Thus, more efficient irrigation methods should be applied in the ASB to mitigate salinization of soil due to evaporation.

In the ASB, proper legislations securing groundwater resources are missing. Thus, new legislations should be developed among countries sharing the ASB to commonly manage groundwater resources, especially transboundary aquifers.

ACKNOWLEDGEMENTS:

Khorezm Rural Advisory Support Service (KRASS) and the Ministry of Agricultural and Water Resources of Uzbekistan are acknowledged for providing observed groundwater level data.

REFERENCES:

1. Abuduwaili, J., Issanova, G., and Saparov, G. (2019). *Hydrology and Limnology of Central Asia*. Singapore: Springer Singapore. https://doi.org/10.1007/978-981-13-0929-8
2. Ahmed, M., & Abdelmohsen, K. (2018). Quantifying Modern Recharge and Depletion Rates of the Nubian Aquifer in Egypt. *Surveys in Geophysics*, 1–23. https://doi.org/10.1007/s10712-018-9465-3
3. Ahmed, M., Sultan, M., Wahr, J., Yan, E., Milewski, A., Sauck, W., et al. (2011). Integration of GRACE (Gravity Recovery and Climate Experiment) data with traditional data sets for a better understanding of the time- dependent water partitioning in African watersheds, (5), 479–482. https://doi.org/10.1130/G31812.1
4. Ahmed, M., Sultan, M., Wahr, J., & Yan, E. (2014). The use of GRACE data to monitor natural and anthropogenic induced variations in water availability across Africa. *Earth-Science Reviews*, *136*, 289–300. https://doi.org/10.1016/j.earscirev.2014.05.009
5. Ahmed, M., Sultan, M., Yan, E., & Wahr, J. (2016). Assessing and Improving Land Surface Model Outputs over Africa using GRACE, Field, and Remote Sensing Data. *Surveys in Geophysics*, *37*(3), 529–556. https://doi.org/10.1007/s10712-016-9360-8
6. Bekturganov, Z., Tussupova, K., Berndtsson, R., Sharapatova, N., Aryngazin, K. and Zhanasova, M. 2016. Water Related Health Problems in Central Asia – A Review, Water, 8. 219; doi:10.3390/w8060219
7. Berkum, S. 2015. Agricultural potential and food security in Central Asia in the light of climate change. Issue Brief, LEI Wageningen UR
8. CAWaterInfo. 2011. *The Aral Sea Basin.*
9. Djanibekov N (2008) A Micro-Economic Analysis of farm restructuring in the Khorezm Region, Uzbekistan. PhD thesis, University of Bonn.
10. Dukhovny, V., Umarov, P., Yakubov, H. and Madramootoo, Ch. 2007. Drainage in the Aral Sea Baisn, Irrigation and Drainage, 56; 91-100.
11. Cuthbert, M. O., R. I. Acworth, M. S. Andersen, J. R. Larsen, A. M. McCallum, G. C. Rau, and J. H. Tellam. 2016., Understanding and quantifying focused, indirect groundwater recharge from ephemeral streams using water table fluctuations, *Water Resour. Res.*, 52, 827–840, doi:10.1002/2015WR017503.

12. Ebead, B., Ahmed, M., Niu, Z., & Huang, N. (2017). Quantifying the anthropogenic impact on groundwater resources of North China using Gravity Recovery and Climate Experiment data and land surface models. *Journal of Applied Remote Sensing*, *11*(2), 026029. https://doi.org/10.1117/1.JRS.11.026029
13. Fallatah, O. A., Ahmed, M., Save, H., & Akanda, A. S. (2017). Quantifying Temporal Variations in Water Resources of a Vulnerable Middle Eastern Transboundary Aquifer System. *Hydrological Processes*. https://doi.org/10.1002/hyp.11285
14. Fallatah, O. A., Ahmed, M., Cardace, D., Boving, T., & Akanda, A. S. (2018). Assessment of Modern Recharge to Arid Region Aquifers Using an Integrated Geophysical, Geochemical, and Remote Sensing Approach. *Journal of Hydrology*. https://doi.org/10.1016/J.JHYDROL.2018.09.061
15. FAO, 2013. Irrigation in Central Asia in figures, AQUASTAT Survey-2012. FAO Water Reports 39
16. Forkutsa, I., Sommer, R., Shirokova, I., Lamers, J., Kienzler, K., Tischbein, B., Martius, C. and Vlek, B. Modeling irrigated cotton with shallow groundwater in the Aral Sea Basin of Uzbekistan: I. Water dynamics
17. Friedrich, J. (2009). Uranium contamination of the Aral Sea. *Journal of Marine Systems*, *76*(3), 322–335. https://doi.org/10.1016/j.jmarsys.2008.03.020
18. Ibragimov, N., Everett, R. S., Esanbekov, U., Kamilov, B. S., Mirzaev, L., and Lamers, J. P. A.. 2007. Water use efficiency of irrigated cotton in Uzbekistan under drip and furrow irrigation. Agricultural Water Management, 90(1-2): 112-120.
19. Ibrakhimov, M. 2004. Spatial and temporal dynamics of groundwater table and salinity in Khorezm (Aral Sea Basin), Uzbekistan. Ecology and Development Series 24, Cuvillier Verlag. Göttingen.
20. Karimov, A., Smakhtin, V., Mavlonov, A., Borisov, V., Gracheva, I., Miryusupov, F., Akhmedov, A., Anzelm, K., Yakubov, S. and Karimov, A. Managed Aquifer Recharge: Potential Component of Water Management in the Syrdarya River Basin, Journal of Hydrologic Engineering, 2014.
21. Kløve, B., Ala-Aho, P., Bertrand, G., Gurdak, J.J., Kupfersberger, H., Kværner, J., et al., 2014. Climate change impacts on groundwater and dependent ecosystems. J.Hydrol. 518, 250-266.
22. Jarsjö, J., & Destouni, G. (2004). Groundwater discharge into the Aral Sea after 1960. *Journal of Marine Systems*, *47*(1–4), 109–120. https://doi.org/10.1016/j.jmarsys.2003.12.013
23. Lee, E., Jayakumar, R., Shrestha, S. and Han, Z. Assessment of transboundary aquifer resources in Asia: Status and progress towards sustainable groundwater management. Jounral of Hydrology: Regional Studies, 2018.
24. Niyazi, B. A., Ahmed, M., Basahi, J. M., Masoud, M. Z., & Rashed, M. A. (2018). Spatiotemporal trends in freshwater availability in the Red Sea Hills, Saudi Arabia. *Arabian Journal of Geosciences*, *11*(22), 702. https://doi.org/10.1007/s12517-018-4052-y
25. Micklin, P. (2016). The future Aral Sea: hope and despair. *Environmental Earth Sciences*, *75*(9), 844. https://doi.org/10.1007/s12665-016-5614-5
26. Ministry of Energy, K. (2017). *Information bulletin on the Environment and human health in Aral Sea basin: 2017*. Retrieved from ttps://kazhydromet.kz/upload/pdf/ru_1516180142.pdf
27. NATO, 2016. Proceedings of the NATO Advanced Research Workshop on The Socio-Economic Causes and Consequences of Desertifi cation in Central Asia, Bishkek, Kyrgyzstan
28. Oberhänsli, H., Weise, S. M., & Stanichny, S. (2009). Oxygen and hydrogen isotopic water characteristics of the Aral Sea, Central Asia. *Journal of Marine Systems*, *76*(3), 310–321. https://doi.org/10.1016/j.jmarsys.2008.03.019
29. Ostrovsky VN (2007) Comparative analysis of groundwater formation in arid and super-arid deserts (with examples from Central Asia and Northeastern Arabian Peninsula). Hydrogeology Journal
30. Panichkin. V., Miroshnichenko, O., Zakharova, N., A.Satpayev, Trushel, L., Kalmykova, N., … Veselov, V. (2011). ll. EASTERN PRIARALYE GROUNDWATERS. Retrieved February 14, 2019, from http://old.unesco.kz/water/ar_ch_2_r.htm

31. Rakhmatullaev, Sh., Huneau, F., Kazbekov, J., Le Coustumer, Ph., Jumanov, J., El-Oifi, B., Motelica-Heino, M. and Hrkal, Z. 2010. Groundwater resources use and management in the Amu Datya River Basin (Central Asia), 59:1183-1193. DOI 10.1007/s12665-009-0107-4
32. Schettler, G. et al. Hydrochemical water evolution in the Aral Sea Basin. Part I: Unconfined groundwater of the Amu Darya Delta – Interactions with surface waters, 2013
33. Tapley, B. D., Bettadpur, S., Ries, J. C., Thompson, P. F., & Watkins, M. M. (2004). GRACE measurements of mass variability in the Earth system. *Science*, *305*(5683), 503–5. https://doi.org/10.1126/science.1099192
34. UNESCO-IHP 2016, Governance of Groundwater Resources in Transboundary Aquifers (GGRETA), Main achievements and Key Findings
35. UNESCO-IHP-WINS – The Water Information Network System (access date: 25.01.2019)
36. UN-IGRAC-2018. International Groundwater Resources Assessment Centre.
37. Wang, P., Yu, J., Zhang, Y., Liu, C., 2013. Groundwater recharge and hydrogeochemical evolution in the Ejina Basin, northwest China. Journal of Hydrology. 476, 72-86.
38. World Bank, 2013. Irrigation in Central Asia. Social, Economic and Environmental Considerations.
39. Panichkin V., Sagin J., Miroshnichenko O., Trushel L., Zakharova N., Yerikuly Z. & Livinskiy Y., Assessment and forecasting of the subsurface drain of the Aral Sea, Central Asia, International Journal of Environmental Studies Vol. 74 , Iss. 2, 2017
40. Zhiltsoz, S., Zonn, S., Kostinanoy, I and Semenov, A. Water Resources in Central Asia: International Context. The handbook of environmental chemistry. Springer 2018.