
Comparative analysis of groundwater formation in arid and super-arid deserts (with examples from Central Asia and northeastern Arabian Peninsula)

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Abstract Groundwater formation within arid and super-arid deserts is discussed through comparative analysis. Although fresh groundwater is being formed in both types of deserts, mainly from infiltrated surface runoff, in arid deserts, infiltration is currently taking place, whereas in super-arid areas, it occurred mainly in the Pleistocene pluvial epoch. Groundwater discharge conditions are also different. In arid deserts, the discharge occurs mainly through transpiration by phreatophytes, which form phyto-hydrogeological ecosystems where the dominant factor is an interaction between groundwater and vegetation, with transpiration reaching over hundreds of mm/year and the thickness of the groundwater evaporation zone extending over 10m. Active subsurface water exchange does not favor the preservation of Pleistocene fossil groundwater. Super-arid deserts, however, have an extremely scarce vegetative cover (low, if any), physical evaporation, a thin zone of evaporation influence, and slow water outflow. Favorable conditions therefore exist for the preservation of relict low-mineralized waters. Furthermore, arid and super-arid deserts differ by types of groundwater accumulation and horizontal and vertical zonalities. In arid deserts, hydrogeological problems are connected with the anthropogenic influence upon groundwater, and with control on rational use of surface water and groundwater. In super-arid deserts, the basic problem is depletion of fossil groundwater.

Résumé La formation d'eaux souterraines dans les déserts arides et super arides est discutée à travers une analyse comparative. Bien que l'eau souterraine douce soit formée dans les deux types de déserts, surtout à partir des ruissellements de surface qui s'infiltrant, l'infiltration dans

les déserts arides est courante alors qu'elle fut courante dans le deuxième cas lors de l'époque pluvieuse du Pléistocène. Les conditions de déversement des eaux souterraines sont également différentes. Dans les déserts arides le déversement apparaît essentiellement via la transpiration des phréatophytes, qui forment des écosystèmes phyto-hydrogéologiques où le facteur dominant est une interaction entre l'eau souterraine et la végétation, la transpiration pouvant atteindre plusieurs centaines de mm/an et une épaisseur de la zone d'évaporation qui s'étend sur plus de 10m. Les échanges actuels d'eau en subsurface ne favorisent par la préservation des eaux souterraines fossiles du Pléistocène. Les déserts super-arides, cependant, possèdent une couverture végétale très rare et une faible évaporation physique si il en existe une, une zone d'influence de l'évaporation très mince, et des écoulements d'eau très lents. Les conditions sont dès lors favorables pour la préservation d'eaux relictées à faible minéralisation. De plus, les déserts arides et super-arides diffèrent par les types d'accumulation des eaux souterraines et par les zonalités horizontales et verticales. Les problèmes hydrogéologiques dans les déserts arides sont connectés à une influence anthropogénique des eaux souterraines, et à un contrôle de l'utilisation rationnelle des eaux de surface et souterraines. Dans les déserts super-arides le problème de base est la diminution des eaux souterraines fossiles.

Resumen La formación de Agua subterránea dentro de los desiertos áridos y súper-áridos se discute a través del análisis comparativo. Aunque el agua subterránea dulce está formándose en ambos tipos de desierto, principalmente a partir del escurrimiento superficial infiltrado, la infiltración de los desiertos áridos está ocurriendo actualmente, mientras que en las áreas súper-áridas ocurrió principalmente en la época lluviosa Pleistocena. Las condiciones de la descarga de agua subterránea también son diferentes. En los desiertos áridos la descarga ocurre principalmente a través de la transpiración por freatofitas, que forman ecosistemas fito-hidrogeológicos, donde el factor dominante es una interacción entre el agua subterránea y vegetación con transpiración que alcanza centenares de mm/año y el espesor de la zona de evaporación de agua subterránea se extiende por encima de 10m. El intercambio activo de agua subsuperficial no favorece la preservación del agua subterránea pleistocén-

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ica fósil. Sin embargo, los desiertos súper-áridos, tienen una cubierta vegetativa sumamente escasa; evaporación física baja, si esta existe; una zona delgada de influencia de evaporación, y salida de agua lenta. Existen por consiguiente, condiciones favorables para la preservación de relictos de agua con baja mineralización. Además, los desiertos áridos y súper-áridos difieren por los tipos de acumulación del agua subterránea y la zonalidad horizontal y vertical. En desiertos áridos, los problemas hidrogeológicos están conectados con la influencia antropogénica en el agua subterránea, y con el control en el uso racional del agua superficial y subterránea. En los desiertos súper-áridos el problema básico es el vaciamiento de agua subterránea fósil.

Keywords Arid regions · Groundwater recharge · Evaporation · Precipitation · Runoff

Introduction

The main goal of the study is to characterize the hydrogeological differences between arid and super-arid areas caused by landscape-climatic factors. Therefore, descriptions of the geologic-tectonic, orographic and other features of such areas are only given very briefly.

Arid regions do not have uniform climatic conditions although they are often referred to generally as areas where potential evaporation (evaporability) exceeds precipitation.

Meigs (1953) divided arid regions into three groups: semi-arid, arid and super-arid, which differ from each other by Thornthwaite's indices (Thornthwaite 1948) and their precipitation regimes. It would be expected, that with a decrease in moistening degree and an increase in potential evaporation, fresh groundwater resources should be decreasing from semi-arid latitudes towards super-arid ones. However, this does not appear to be the case everywhere. In some super-arid regions, the resources of low-mineralized groundwater are greater than in some regions that are wetter (e.g. the Caspian Sea basin, Ustyurt basin, both in Asia). Such anomalies are due to both local hydrogeological features and other factors such as tectonics, paleo-climate, and vegetation.

It can be clearly seen on geographical maps that the majority of deserts border onto mountainous structures and this includes the examples described in this report: the deserts of Central Asia are adjacent to the mountainous ridges of Tian Shan, Pamirs and Copet Dag; and the deserts of the northeastern Arabian Peninsula are adjacent to the mountains of Oman.

The juxtaposition of mountains and deserts exerts a great influence upon hydrogeological conditions, thus favoring the formation of considerable groundwater resources in a number of arid regions. The proximity of mountains and deserts, which is typical of arid zones, determines the existence of two subtypes of groundwater formation in arid conditions: autochthonous and allochthonous (Ostrovsky 1966).

The autochthonous subtype is developed in regions not influenced by mountainous systems and is characterized by groundwater formation from in situ water resources, and mainly from precipitation. The total water balance in steady-state conditions is described by Eq. (1), and the balance of groundwater in steady-state conditions by Eq. (2):

$$E = P \quad (1)$$

$$E_w = P_w \quad (2)$$

where E and P are, respectively, the evaporation (evapotranspiration) and precipitation within the arid zone; E_w and P_w are, respectively, the groundwater evaporation and groundwater recharge from precipitation within this region. The P_w value can include, besides infiltrated precipitation, condensation recharge which is usually observed in littoral deserts.

The allochthonous subtype is typical of deserts where groundwater is formed under the influence of mountainous systems. It is commonly held that arid zones are characterized by the presence of basins that have no runoff to the ocean and where all precipitation is used up through evapotranspiration. However, if arid zones are considered within their climatic boundaries, then the balance of precipitation and evaporation cannot be true, as the total amount of evaporation also includes evaporation of both surface runoff and groundwater discharge from mountainous humid regions. Therefore, in general, the water balance in steady-state conditions can be written as:

$$E = P + R \quad (3)$$

where E and P are, respectively, the evaporation and precipitation within the arid zone; R is the surface run-off and groundwater discharge flowing from humid regions to deserts.

The groundwater balance in steady-state conditions can be expressed as:

$$E_w = P_w + R_w \quad (4)$$

where R_w is the groundwater recharge from surface and groundwater flowing from humid regions.

It should be noted that Eqs. (3) and (4) are typical not only of the present interglacial period. During glacial epochs, modern deserts had a higher moisture content (Alsharhan et al. 1963), which favored the accumulation of considerable groundwater resources, some of which are still preserved today as relict (fossil) waters.

The main input to the formation of allochthonous groundwater is surface run-off.

The vegetation cover in arid areas can be clearly differentiated into two ecological groups (Meinzer 1947): phreatophytes (plants consuming groundwater) and plants consuming atmospheric moisture.

It is usually considered that in arid zones, vegetation mainly influences groundwater discharge, which occurs via transpiration. However, vegetation significantly influences groundwater recharge as well. Arid deserts are characterized by the presence of ecological-hydrogeological (phyto-hydrogeological) systems, the structure, state and dynamics of which are determined chiefly by hydrogeological factors (Ostrovsky 1982). In spite of the low biological productivity of the vegetation and low projective cover, the systems serve as one of the determinant factors in the formation of groundwater resources. Phyto-hydrogeological systems are not typical of super-arid deserts.

The report presents the comparative analysis of groundwater formation in arid deserts (using examples from Central Asia) and deserts with a super-arid climate (using examples from the northeastern region of the Arabian Peninsula). For many years, the author has participated in hydrogeological investigations of the arid deserts in Central Asia and the given analysis is based on his own experience. The hydrogeological characteristics of super-arid deserts are described using data from the

literature. However, not all the problems presented in the given report have found a final solution; therefore, investigations in this field should be continued.

Specific features of groundwater formation in arid deserts (based on examples from Central Asia)

Landscape-geological and hydrogeological features

According to the classification of Meigs (1953), the deserts of Central Asia belong to the group with arid climates, i.e. with a Thornthwaite's index of below 40, but with an annual precipitation varying from 100 to 200 mm. The hydrogeological features of the deserts in Central Asia are well studied and described in a great number of publications. Among them, of particular note, is the 48-volume monograph *Hydrogeology of the USSR* (IHEG 1971–1976) and *Atlas of Hydrogeological and Geological Engineering Maps of the USSR* (Rogovskaya 1984).

The region is characterized by very complicated hydrogeological conditions. The hydrogeological zoning is schematically shown in Fig. 1 (after Rogovskaya (1983)

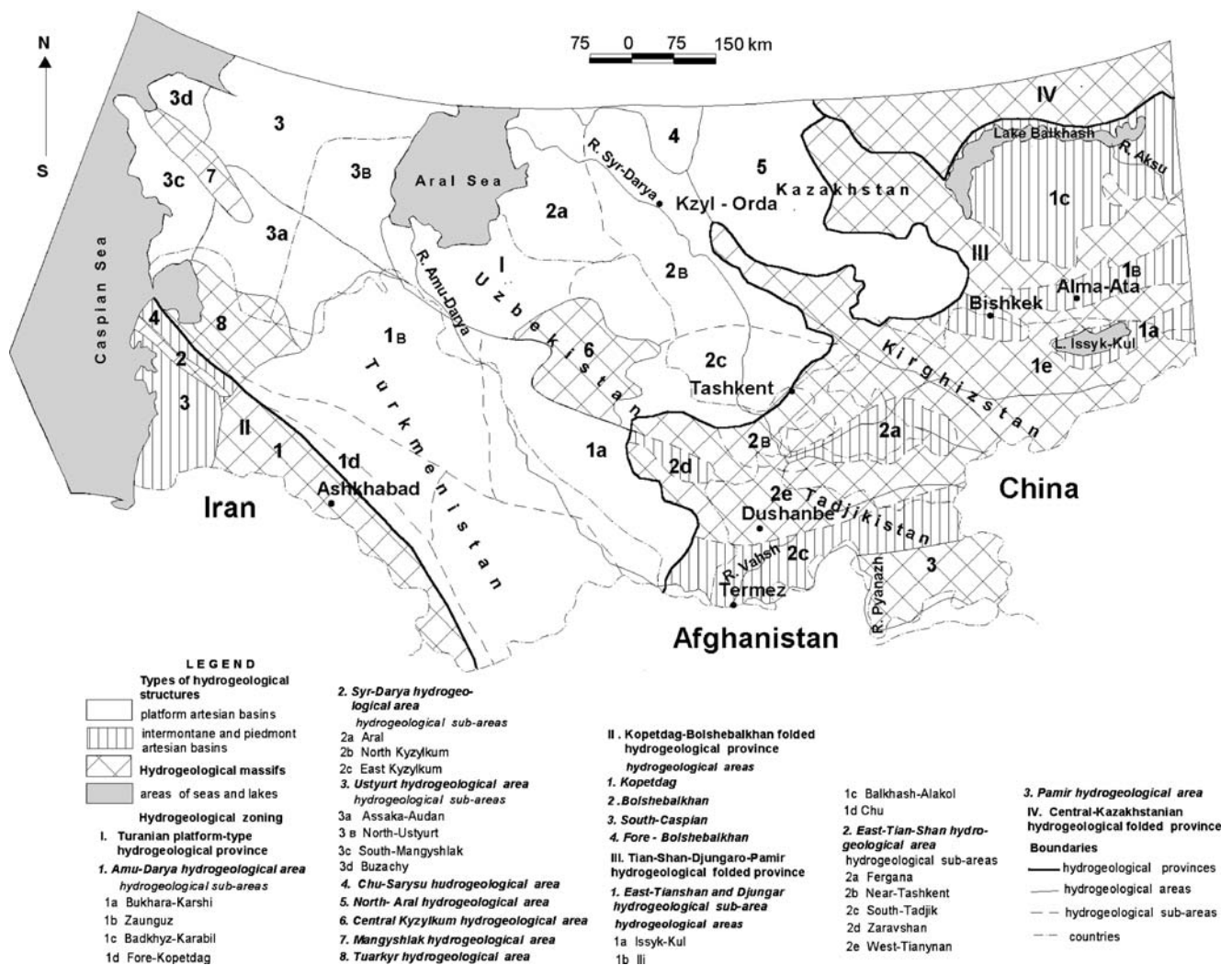


Fig. 1 Map of the hydrogeological zoning of Central Asia (modified, Rogovskaya (1983))

with some modifications by the author). Three types of hydrogeological structures are distinguished on the map:

- Platform-type artesian basins
- Intermontane and piedmont artesian basins
- Hydrogeological massifs (basins of fissured and fissure-karst waters)

This classification has served as the basis for regional hydrogeological zoning. The regions of the first order (provinces) include the hydrogeological basins of Turanian Plate (I); Kopetdag-Bolshebalkhanskaya (II), Tianshan-Djungaro-Pamir (III) and Central-Kazakhstanian (IV) hydrogeological folded areas. Within the regions of the second order are large platform-type artesian basins and parts of the hydrogeological folded areas. Some artesian basins or hydrogeological massifs that possess a certain autonomy, are referred to as the regions of the third order.

The Turanian province is located wholly within an arid zone chiefly with a plain relief. Landscapes of sandy, *solonchak* (salted soil) and sometimes piedmont deserts dominate there. As a rule, the artesian basins are composed of thick (up to several kilometers) strata of terrigenous sediments. Most promising for practical use are the aquifers in the molassa formations of Quaternary and Neogene periods (chiefly gravels, pebbles, sand), as well as in the Quaternary eolian sediments. Confined waters are widely spread in Cretaceous sediments (mainly sands). The molassa formations contain chiefly fresh waters, whereas the Quaternary eolian, Cretaceous and other water-bearing rocks include waters with an increased mineralization of up to 10 g/l and higher, though fresh waters are also encountered. The Turanian province also includes structures of the massif type (Central Kyzylkum, etc.). Topographically, they are arid mountains composed mainly of Paleozoic, Mesozoic and Cenozoic terrigenous and carbonate rocks containing limited groundwater resources.

The Kopetdag-Bolshebalkhanskaya and Tianshan-Djungaro-Pamir hydrogeological provinces have a certain commonality. Namely, they are recharge areas of surface and groundwater of the Turanian Plate. Distribution and formation of groundwater is controlled by vertical landscape zonality and rupture tectonics.

Massifs represent the predominant type of hydrogeological structures, the majority of which are located beyond the arid zone. Only intermontane and piedmont basins of the third order (Fergana, Issyk-Kul, etc.) can be referred to arid areas. The Central-Kazakhstanian province is a large hydrogeological massif isolated from the Turanian Plate.

This report gives only a brief hydrogeological description of Central Asia. It should be noted, however, that the hydrogeological massifs have a direct vertical hydrogeochemical zonality, i.e. groundwater mineralization increases with depth. In the artesian basins, the vertical hydrogeochemical zonality is reversed, i.e. groundwater mineralization decreases with depth to a few hundred meters. An example of this is shown in Fig. 2. The

reversed zonality occurs chiefly due to evaporation from the surface of groundwater fluxes.

It should be noted that fossil waters have a limited areal extent and are found in the west of the region, in the Amu-Darya River artesian basin (e.g. Yaskhanskaya, Djillikumskaya lenses and others; Shevchenko 1963).

Groundwater recharge

In the modern epoch, the allochthonous subtype of groundwater formation is prevailing. The basic source of groundwater recharge is allochthonous river run-off. Thus, according to Khodzhibaev (1970), 529 m³/sec or 86.5% of the total natural groundwater recharge (612 m³/sec) in Uzbekistan comes from the rivers. A relationship is observed between the amounts of groundwater replenishment and river run-off. An example of such a relationship is illustrated in Fig. 3 (Ostrovsky 1991).

The Central-Asian region is characterized by the formation of large allochthonous underground flows

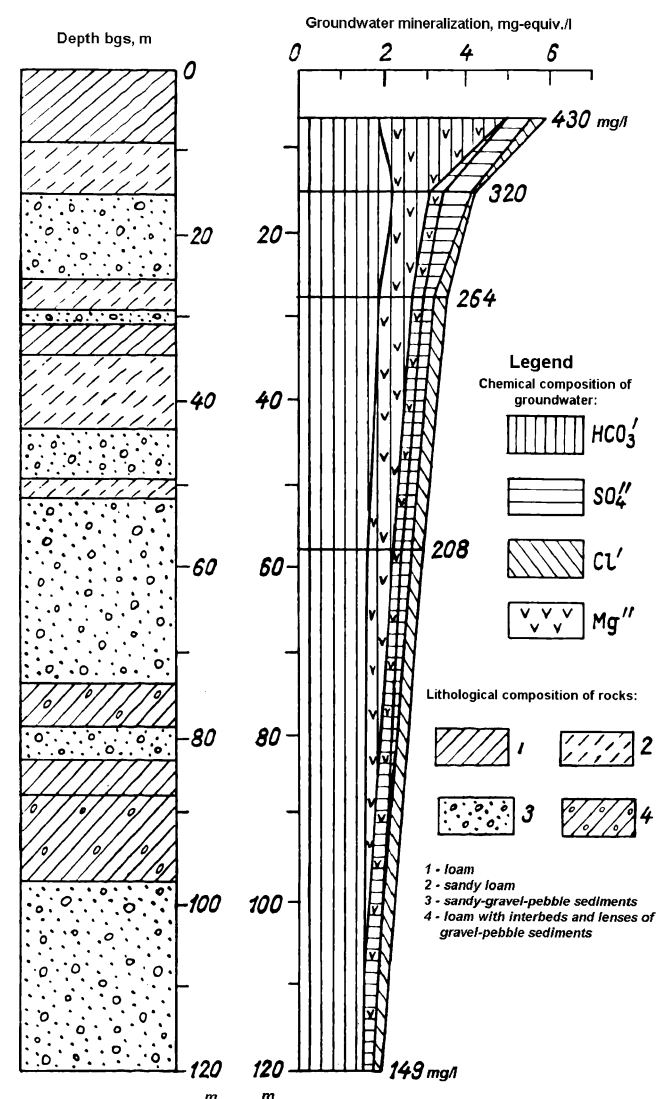
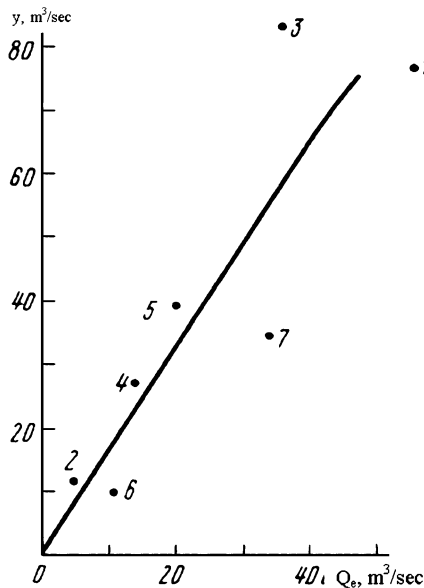


Fig. 2 Vertical hydrochemical zonality of confined groundwater, Balkhash-Alakolsky basin (modified, Ostrovsky 1979)



- 1 an intermontane basin on the northern slope of Zailisky Alatau;
 2 the basin of River Aksu debris cone on the northern slope of Djungarsky Alatau;
 3 Alakolsky intermontane basin; 4 Talassky piedmont basin;
 5 eastern part of the Ilisky intermontane basin;
 6 piedmont basin on the northern slope of Ketmen Ridge;
 7 - Zaisansky intermontane basin.

Fig. 3 Relationship between the river run-off (y) and natural groundwater resources Q_e in the areas of southern Kazakhstan (modified, Ostrovsky 1991)

penetrating deep into the deserts. This is one of the typical hydrogeological features of the region. A detailed description of the groundwater flow in Uzbekistan was given by Khodzhibaev (1970). Besides the sub- and intermontane plains, where the major fresh groundwater resources are being formed, an intensive recharge of groundwater by surface waters is also taking place in the deltas of large rivers. In such deltas, one can observe complex systems of numerous river channels composed of modern and ancient alluvium. The channels are often changing due to instability in the hydrographic network.

So, in certain cases, surface run-off helps to accumulate large fresh groundwater resources. For example, in the Ili River delta in the Quaternary sandy sediments, a water-bearing system of over 200 m thick and water transmissivity of over 1,000 m²/day has been formed, which greatly influences the landscape of the adjacent Desert Sary-Ishik-Otrau over a distance of hundreds of kilometers (Ostrovsky 1976).

As compared with surface water run-off, the underground water inflow from regional and local groundwater recharge areas plays a minor role in the groundwater balance. The author regards, sceptically, the possibility of great amounts of groundwater penetrating to deserts through tectonic disturbances, although in some cases this can be significant (Ostrovsky 1991). Groundwater recharge occurring at the expense of surface run-off varies, on average, from 100 to 300 mm/year, reaching sometimes

500–800 mm/year (*Atlas of Hydrogeological and Geological Engineering Maps of the USSR*; Rogovskaya 1984).

Groundwater recharge resulting from infiltrated precipitation is of minor importance in the water balance compared with the surface run-off; but, in terms of recharge quantity, surface run-off is considerably less. Atmospheric recharge joins the allochthonous underground water flow and becomes highly significant in the sandy deserts occupying the major part of this region. Infiltration of atmospheric moisture into the eolian water-bearing sands was studied by experimental investigations of moisture transfer to the unsaturated zones, and also using hydrogeodynamic and stationary balance methods (Chubarov 1972).

The investigations have shown that the groundwater recharge greatly depends on vegetation. As a rule, recharge areas are located in barchan sands free of vegetation. It was determined by an experimental method of Chubarov (1972), that the recharge value in the barchan sands of the Karakum desert, amounts, on average, to 6.8 mm/year at a groundwater depth of over 3 m. At shallower depths, the barchan sands are overgrown with plants, thus limiting recharge of groundwater. In sands overgrown with plants, the infiltration recharge is considerably lower than 6.8 mm/year or is not present at all. The infiltration process occurs under the action of gradients of moisture and temperature.

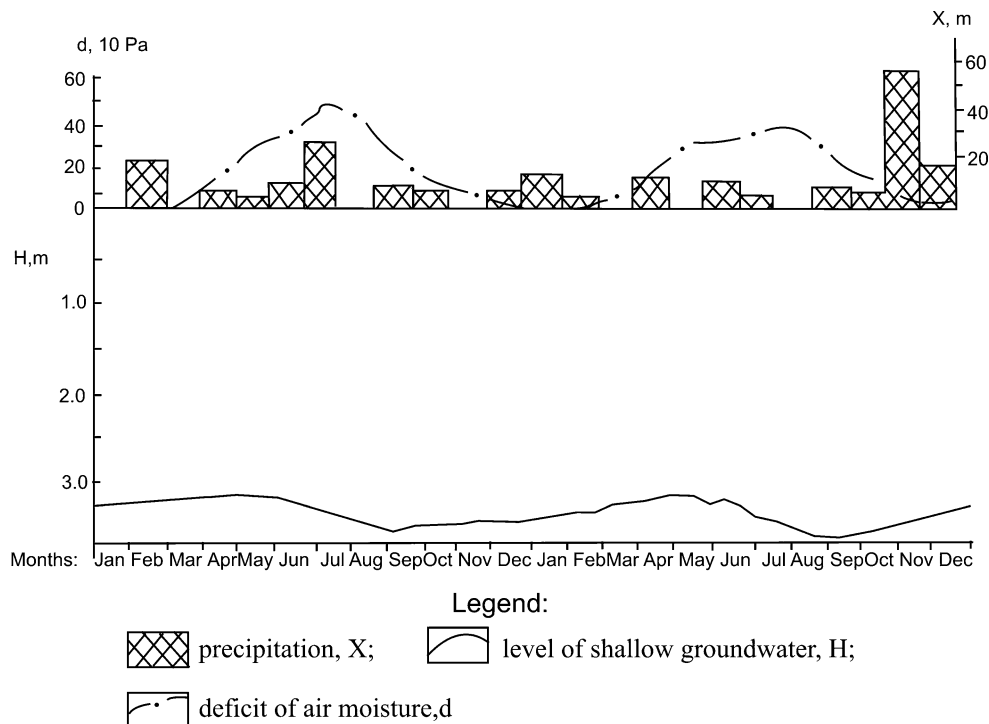
As monitoring observations show, in the sandy deserts of Moyunkum and Sary-Ishik-Otrau in the Manghyshlak Peninsula, where groundwater lies at a depth of over 3 m, a steady rise of groundwater level of 0.1–0.3 m begins in October or November when plant vegetation has ceased growing, independent of whether precipitation falls or not. This rise lasts until May or June (Fig. 4).

The intensity of groundwater recharge also depends on the seasonal rhythms of plant vegetation and precipitation regime and the following relationships are possible:

1. Effective precipitation (i.e. precipitation which infiltrates into aquifers) happens during a period with positive temperatures and intensive plant vegetation. Thus, in the south of the Karakum desert, the precipitation peak occurs in springtime when a highly productive vegetative cover is developing, composed mainly of ephemerals, i.e. plants with a short spring period of vegetation. The absolute infiltration groundwater recharge decreases drastically.
2. Infiltration recharge of groundwater happens in a period with low temperatures and a low productivity of vegetation (e.g. deserts of the Kazakhstanian type). In this case, if geologic-geomorphologic conditions are favorable, even scanty precipitation can cause relatively intensive infiltration recharge of groundwater.

Low-mineralized fossil groundwater was detected in limited areas, namely in the Cretaceous aquifers of the Syr-Darya River artesian basin, and in the so-called sub-sandy lenses of fresh waters located mainly in the western Karakum (Shevchenko 1963). An example of this is the

Fig. 4 Change in rock moisture content of the unsaturated zone, shallow groundwater level (meters below ground surface) and meteorological elements during 1971–1972 in the Sausiyan sand massif (Mangyshlak; modified, Ostrovsky 1991)



Yaskhanskaya lens, having an ellipsoidal shape with axes of 65 and 30 km and a thickness of the fresh-water zone in the central part of over 80 m. The age of fresh water in the Yaskhanskaya lens is 6,000–7,000 years (Ferronsky et al. 1984). The lens was formed in the ancient valley of the Amu-Darya River. A considerable part of the Yaskhanskaya and other sub-sandy lenses is covered by wood and shrub-type vegetation, which excludes intensive infiltration recharge of the groundwater.

It can be assumed that further detailed investigations would detect new areas of fossil groundwaters in the region. However, it can be said with certainty that these waters will be auxiliary sources of water supply in this region.

Groundwater discharge

Discharge of groundwater proceeds chiefly through transpiration of plants. The depth, to which the root system of phreatophytes reaches, is large. Thus, according to Vostokova (1980), the roots of *Glycyrrhiza glabra*, *Haloxylon persicum*, and some other plants, reach a depth of 30–40 m, which leads to a considerable increase in the thickness of the active water- and salt-exchange zone in the “earth’s surface-shallow groundwater” system. Similar occurrences are also observed in other arid deserts, particularly in the Kalahari desert of South Africa.

Phyto-hydrogeological systems are widely spread mainly in areas with shallow groundwater. The total value of transpiration can exceed potential evaporation, which is determined by penetration of solar energy to the earth’s surface. According to the data of Kats (1976) obtained during observations from lysimeters in the Bukhara oasis

(Uzbekistan), the evaporation of shallow groundwater, at its depth of 1.5 m, is equal to 2,400 mm/year. This value is considerably higher than the maximum evaporation that is possible due to direct penetration of solar radiation to the earth’s surface, which varies between 1,250 and 1,500 mm/year (*Atlas of the World Water Balance*, Rogovskaya 1974). Such a discrepancy can be explained by advection of heat from surrounding areas.

Large-scale heat advection takes place under natural conditions and chiefly in hydromorphic landscapes associated usually with river valleys and groundwater discharge areas, some of which are surrounded by areas of desert. Thus, according to Rodin (1984), in the lower course of the Vakhsh River (Tajikistan) in the *tugais* (i.e. flood-plain forests of the river valley predominantly covered with *Erianthus purpureus*), the productivity of only surface plant biomass reaches 300 metric tonne/ha. The maximum possible biological productivity, estimated by zonal values of the radiation balance, amounts to only 70–80 tonne/ha (Budyko 1971). It can be stated that the heat advection to groundwater discharge areas leads to a considerable increase in evapotranspiration (Ostrovsky 1979). As the basic consumers of moisture in the discharge areas are the plants (phreatophytes) whose transpiration leads to a decrease in fresh groundwater resources.

Transpiration of phreatophytes also exerts an influence upon the dynamics of groundwater, leading to a lowering of its level and an intensification of the water and salt-exchange. All this results in the formation of highly mineralized waters and highly salted soils.

Intensive evaporation of groundwater via vegetation is accompanied by the accumulation of salts in soils and

groundwater. Beideman et al. (1962) has called these processes 'processes of biological salt accumulation'. The biological salt accumulation leads to alternation (succession) of vegetation and transformation of phyto-hydrogeological systems. Of interest is the fact that in spite of high salt concentrations in the shallow groundwater, the vegetative cover still remains at the final stage of successions.

Modern vegetation-free compacted carbonate-gypsum or salt crusts that would serve as a screen for groundwater evaporation are not typical of the given region. Usually, the final result of a biological salt accumulation is solonchak, containing in its top-layer easily soluble salts, carbonates and gypsum, which form efflorescences and incrustations that are vulnerable to deflation. Solonchak is formed mainly as a result of groundwater inflow from surrounding areas, and because of this, the total evaporation from salt dust of the solonchak exceeds precipitation values. For example, according to Aidarov (1968), the evaporation from the solonchak from the left-hand bank of the Syr-Darya River and with a high content of chloride and sodium salts was equal to 235 mm/year (determined by the heat balance method). With precipitation of 119 mm/year, this gives a ratio of precipitation to evaporation of 0.51.

After having analyzed the above hydrogeological features of the region, it can be concluded that the interaction of groundwater and vegetation plays a significant role in the hydrogeological processes occurring in the zone of free water exchange. Although during the last pluvial epoch the replenishment of groundwater was more intensive than presently; nevertheless, the fresh fossil waters accumulated in the Upper Pleistocene, were replaced by younger seeped waters. An important part of this process was groundwater transpiration by phreatophytes, which intensified vertical water-exchange. In the areas where lateral water-exchange was slight, the fossil waters were subjected to salinization chiefly due to the processes of biological salt accumulation. The resources of fresh groundwater in the deserts of Central Asia are rather large and satisfy in some areas the demands not only for fresh water supply, but for irrigation as well. In the piedmont and intermontane basins (Fergana, Talas, Ili and others), the specific discharge of predicted exploitable groundwater resources exceeds 10 l/sec/km²; in the sandy deserts they vary, on average, from 0.1 l/sec/km² (Karakum) to 2 l/sec/km² (Moyunkum and Sary-Ishik-Otrau deserts; Rogovskaya 1984).

The ecological-hydrogeological problems of the region are connected, foremostly, with the intensive development of irrigated agriculture, for which not only surface, but also in some areas, groundwater resources are used. To a lesser degree, the hydrogeological conditions are affected by other types of human activity, for example, groundwater abstraction for drinking water supply, industrial activity, testing of nuclear weapons, etc.

The extraction of huge amounts of water for irrigation purposes has caused serious disturbances in the natural water-exchange cycles, and has led to the desiccation of

inland water bodies. The basic consequences of anthropogenically induced disturbances in the underground hydrosphere include: formation of new areas of groundwater recharge and discharge over large regions; formation of artificially pressurized water systems; transformation of the water and salt balance of groundwater in a number of basins; contamination of groundwater, especially in sub and intermontane basins; and partial depletion of groundwater. The ecological tendency of all these processes is directed towards desertification, which is vividly demonstrated by the adverse transformation of the ecosystems in the Aral and other regions.

Specific features of groundwater formation in super-arid deserts (based on examples from the northeastern Arabian Peninsula)

The hydrogeological features are analyzed, mainly using examples of regions in the United Arab Emirates, but also with the use of data from Qatar, Bahrain, and the northeast of the Arabian Peninsula.

Landscape-geological and hydrogeological features

Deserts of the northeastern Arabian Peninsula are super-arid, with precipitation varying from 50 to 70 mm/year in sandy deserts and from 100 to 250 mm/year in the mountainous highlands. There are years when there is no precipitation at all. The majority of the region lies within the ancient Arabian tectonic plate, which is bordered in the northeast by the Oman Mountains formed as a result of fault dislocations, caused by a collision of the Hindustanian and Arabian tectonic plates during the period from Cretaceous to Paleogene.

The major part is occupied by the Rub-El-Hali syncline composed of thick (from 5 to 6 km) strata consisting chiefly of carbonate terrigenous rocks ranging in age from the Paleozoic to the present. The predominant landscapes are sandy deserts, which are replaced by gravel-pebble deserts at the foot of the Oman Mountains, and by solonchak-soil deserts near the seacoasts. The vegetative cover is rather scanty and of low productivity, and is actually absent over the majority of the region.

In spite of the fact that tens of thousands of hydrogeological wells have been drilled over the area under study, publications on the hydrogeological regularities are few. The available hydrogeological maps are schematic and do not reflect adequately the regularities in groundwater distribution and formation. For example, Fig. 5 shows the hydrogeological map of the United Arab Emirates, which illustrates geological rather than hydrogeological information. Transmissivity is indicated not for prospective aquifers, but for the entire sedimentary cover which chiefly contains waters with a mineralization of over 10 g/l. The map does not indicate hydrogeological regularities in the upper hydrogeodynamic zone where, as a rule, basic recharge of groundwater occurs.

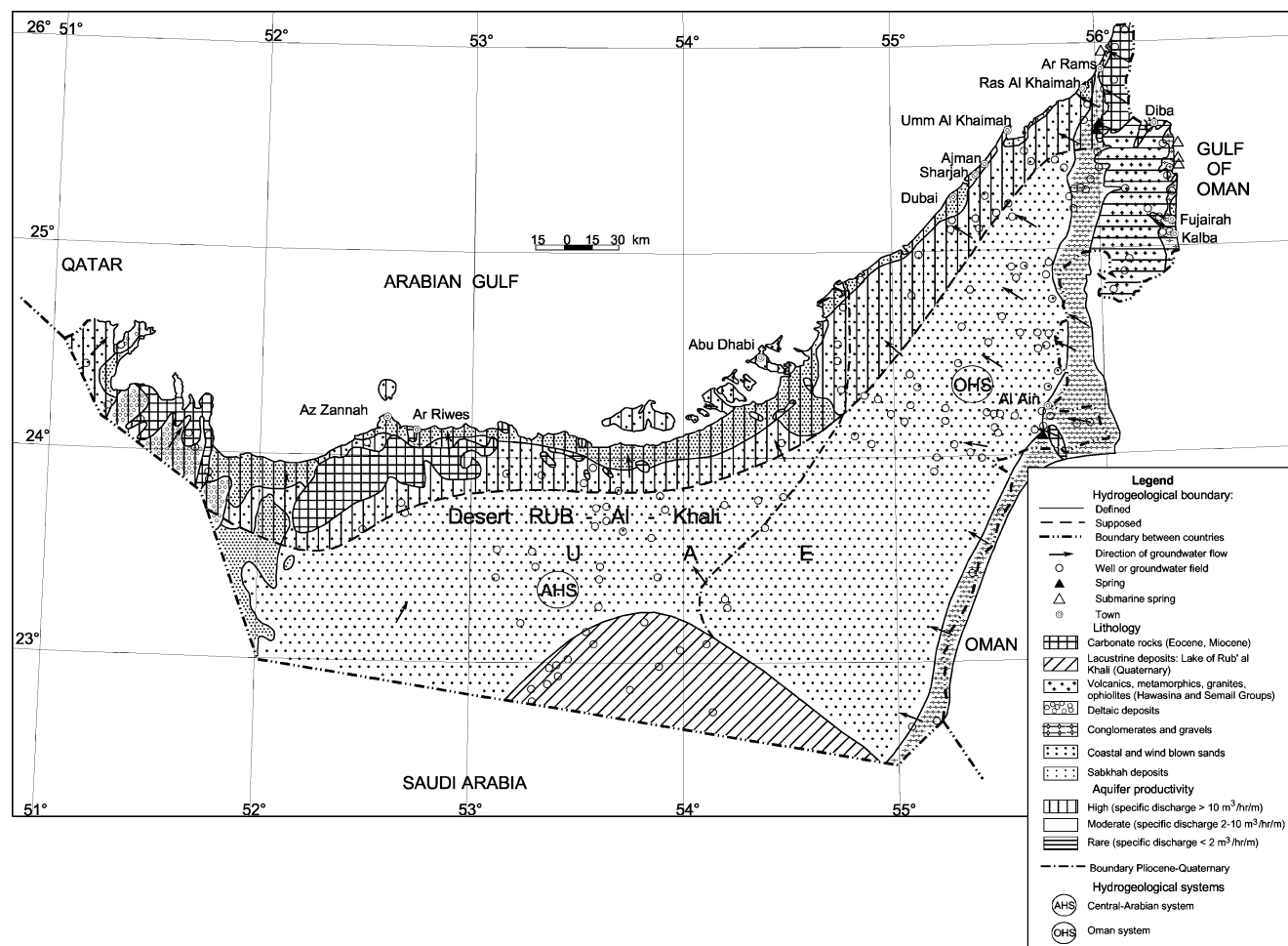


Fig. 5 A hydrogeological map of the United Arab Emirates (UAE; modified, UAE University 1998). The names Arabian Gulf and Persian Gulf are both used in the literature of the region

Therefore, in order to assess the groundwater recharge, the author has had to refer to publications on other super-arid areas. In general, due to the lack of necessary information, some of the author's conclusions are not well enough supported and should be accepted as being up for debate.

The major area under study is within an artesian basin of the Rub-El-Hali syncline, which is characterized by a complicated interbedding of water-bearing and water-tight layers. According to Alsharhan et al. (2001) and other researchers, the Paleozoic, Mesozoic and Cenozoic hydrogeological systems are distinguished in this region. The Paleozoic and Mesozoic systems contain highly mineralized waters and brines. The Cenozoic system has a number of aquifers containing fresh water. The fresh and brackish groundwater is concentrated chiefly in the Quaternary alluvial-pluvial sediments of the piedmont plains of the Oman Mountains. Waters with a mineralization of over 10 g/l prevail in the upper hydrogeodynamic zone. Low-mineralized waters are found locally. The region is characterized by direct vertical hydrogeochemical zonation, i.e. groundwater mineralization increases with depth, although in some particular areas this regularity is disturbed. The formation of direct hydro-

geochemical zonation is promoted by Mesozoic and Cenozoic marine transgression. In the following, the hydrogeological regularities in the upper part of the hydrogeological cross-section are analyzed.

Current fresh groundwater resources are not great due to low atmospheric humidity and super-high potential evaporation. Their distribution depends on tectonics, the features of the Pliocene-Quaternary sedimentation and morphogenesis, as well as on paleogeography. According to study results obtained by Italoconsult Company (1979–1981), Alsharhan et al. (2001) and other researchers, two large geographically separate regional hydrogeological systems—Central Arabian and Oman—are distinguished in the region. In Fig. 5, they are shown according to Sayari and Zötl (1978). The recharge areas of the former system are located in the mountains of the central Arabian Peninsula (Tuwaik Plateau and others), those of the latter, in the Oman Mountains. It should be noted that the above-mentioned systems also involve the deeper parts of the cross-section (Alsharhan and Natim 1997).

The Central Arabian system was actively functioning during the Pleistocene pluvial epoch. At the present time, it consists of a number of paleo-valleys with an extremely

slow groundwater flow towards the Gulf (referred to in the literature of the region as either Arabian Gulf or Persian Gulf). The extremely low intensity of lateral water-exchange is confirmed by the data in the monograph by Italoconsult (1971–1981). It can be seen on the hydrogeological map of the Quaternary upper aquifer system, attached to the monograph, that the hydrogeochemical zonality typical of shallow groundwater flow is not observed everywhere in the Central Arabian system. Thus, for example, in the area of the Tuwaik Plateau (a regional groundwater recharge area) the groundwater has a mineralization of 1–5 g/l, increasing with further groundwater movement to 10 g/l and higher, but in the Liwa oasis at the boundary of Saudi Arabia and the United Arab Emirates the mineralization decreases to 3–4 g/l, and only in the groundwater discharge area along the Arabian/Persian Gulf coast does the salt content reach a few tens of g/l. Water desalinization in the Liwa oasis happens, obviously, owing to atmospheric recharge, with lateral water-exchange being, in this case, zero. According to calculations (Sayari and Zötl 1978), the velocity of groundwater movement does not exceed a few meters per year.

Considering the geological conditions, the Oman system is similar to that in Central Arabia, but has a more active horizontal water-exchange, especially at the eastern slope of the Oman Mountains. Groundwater recharge areas are the Gulf of Oman and the Arabian/Persian Gulf.

Groundwater recharge

A relatively intensive replenishment of groundwater resources is observed mainly in the Oman hydrogeological system. The basic source of groundwater recharge is seepage from temporary surface-water streams (wadis), which occur mainly on the piedmont plains. The contribution of water, seeping from the mountains, to groundwater recharge is small and lower than in the desert regions of Central Asia, as water penetration from the mountains to the water-bearing layers on the plains is blocked by the overthrust tectonics impeding the hydraulic continuity between the mountains and plains (UAE University 1998); hydrogeological cross-section in northern, central and eastern agricultural regions). A direct relationship exists between the groundwater recharge and the precipitation (Alsharhan et al. 2001). In the monograph *Hydrogeology of an Arid Region: The Arabian Gulf and Adjoining Areas* (Alsharhan et al. 2001), the total present-day groundwater recharge in the UAE is reported as equal to 387 million m³/year. As the groundwater recharge in eolian deserts, which occupy 74% of the UAE territory, is not discussed in the monograph, it can be assumed that the above-mentioned recharge value relates to the mountains and adjacent alluvial-pluvial piedmont plains which occupy 26% of the UAE (or 77,000 km²). Thus, taking into consideration the assumptions made above, the total groundwater recharge in the piedmont and mountainous parts of the UAE can be tentatively estimated as 19 mm/year which is considerably lower than in the similar areas of Central Asia.

The atmospheric recharge of groundwater on the UAE plains, which are composed of sandy and solonchak deserts, has not been sufficiently studied but it is likely that a considerable part of the region has local areas where the groundwater receives atmospheric recharge.

Taking into consideration the fact that eolian sands are present over large areas, penetration of atmospheric moisture to the eolian aquifer is very important in a practical respect. Unfortunately, this source of groundwater recharge in the given area has not been studied. According to Dincer et al. (1974), and based on isotope measurements, the eolian aquifer of the central Arabian Peninsula receives about 20 mm of water annually to a depth of about 7 m below surface level. However, whether this water penetrates to underlying aquifers has not been established. According to Dincer (1980), atmospheric recharge depends on the size of sand particles, and such recharge is possible only when the particles are greater than 0.2 mm in diameter. It should be also noted that the atmospheric recharge of groundwater in sandy deserts is increased by the absence of vegetation. Nevertheless, it seems that the recharge value of 20 mm is too high for the given region. Probably, it would be no higher than 5 or 6 mm (by estimates of the author). Predominantly fresh-water accumulations are in lenses lying on the local aquicludes. Widespread occurrence of fresh-water lenses floating on saline waters is unlikely as, due to slow water-exchange, these lenses would become salty under the influence of diffusive processes along the dividing line between fresh and saline waters, and also because of vertical seepage of pressurized saline waters.

The present-day recharge of groundwater in carbonate and evaporite sediments of Tertiary age is studied relatively well in Qatar. It is most intensive in the northern part of the country. The recharge areas are associated with collapsed depressions formed as a result of sinks in the roofs of conduits in the Paleogene limestone and gypsum due to karst formation. The present-day groundwater recharge is confirmed by isotope (Tritium) measurements. According to Yurtsever and Payn (1979), the groundwater age in the Tertiary aquifer of Qatar varies from 152 to 515 years.

Taking into account the low precipitation and amplitude of groundwater variations, which can reach almost 1 m in Qatar, it can be supposed that the groundwater recharge can come partially from the penetration of condensed moisture to the aquifers. Considering this matter in more detail, the role of condensation of water vapor from air in groundwater recharge of deserts is ambiguous. Many researchers do not consider condensation to be a real source for fresh groundwater resources. However, taking into consideration that the study region is located in the area of the Arabian/Persian Gulf, which is an intensive vaporizer affecting the climate in the adjacent areas, condensation as a source of groundwater recharge cannot be ignored. It is known that in Abu-Dabi, Dubai, Dokha and other littoral towns of northeastern Arabia, high air humidity and often abundant dew fall-out is observed during the hottest months. This is not the case in Central Asia. The climate of the study region, unique

because of the conditions of atmospheric moisture condensation, is illustrated by the curves in Fig. 6 plotted using the data from the meteorological stations of Al-Batin Airport near the city of Abu-Dabi, see Fig. 5 (UAE University 1998) and, for comparison, from the meteorological station in Termez, southern Uzbekistan (IHEG 1971–1976, volume XXXIX, Uzbekistan).

It can be seen from the comparison in Fig. 6 that the absolute humidity of the air or the moisture content within it is considerably higher in Al-Batin than in Termez. In summertime, when the air moisture reaches its maximum concentration, the relative air moisture content in Al-Batin is equal to about 60%, whereas in Termez, it is only 36%, i.e. a factor of 1.5 lower. The absolute air moisture in the summer months in Al-Batin exceeds 30 mb (millibar), whereas in Termez it is between only 13.5 and 16.5 mb. As tentative estimates show (Sayari and Zötl 1978), at air temperatures of below 40°C and a relative moisture content below 50%, no condensation occurs, which is typical of Termez. However, the condensation degree can potentially reach 10 mm/day and higher at air temperatures of +50°C and relative moisture of about 70%, which is observed often in the littoral deserts of Arabia.

It is true that the majority of condensed moisture is evaporated before reaching shallow groundwater levels. In karst rocks, where there is a large contact area of rock

voids with the atmosphere, condensation can be considerably higher than in *sabkha* (soils with a high salt content and bare of vegetation). The issue of condensation recharge of groundwater in these regions requires more detailed investigation.

Water inflow from beneath cannot be considered as a real source of fresh groundwater formation over the majority of the area as the region has a direct hydro-geochemical zonality, and the artesian waters there are characterized by a high mineralization. Penetration of the artesian waters leads to salinization of the fresh-water aquifers. This is discussed further below. The lateral underground run-off due to low rock transmissivity in the upper aquifers, and, moreover, to the extremely low hydraulic gradients (lower than 0.0001) is also small. In the following, some considerations concerning the conditions of fossil low-mineralized groundwater formation are presented.

According to Edgell (1990), in the desert of Rub-El-Hali of the Holocene period, alternating super-arid and arid epochs have prevailed over the last 6,000 years. The period 6,000–10,000 years ago was a humid (pluvial) epoch when the existing paleo-hydrographic network was formed. During the pluvial epoch, the Central Arabian hydro-geological system was actively functioning. Large rivers such as Ad Davaisir and As Sahara existed in the northeast of Arabia. The rivers were flowing into the Arabian/Persian Gulf; their ancient deltas are still preserved on the coast. In the river valleys, fresh-water resources accumulated, which were subjected later to salinization, as indicated by a *sabkha* zone lying along the paleo-valleys. It should be noted that the paleo-rivers located at 53° east did not carry their water north to the Arabian/Persian Gulf. Instead, the water accumulated in a large paleo-lake near the depression “Mutadion”. Obviously, the lake originated due to neotectonic uplifts formed north of the Liwa oasis. Now, the areas of lacustrine sediments are occupied by *sabkha*, covered (as established by aerocomic photos) with a gypsum layer preventing evaporation. It can be supposed that in the lacustrine sediments, the fossil waters have been preserved and are currently used for water supply. New fresh infiltrated waters in high dunes are also used for water supply. Prediction of areas with buried fossil water should be made through analyzing the historical development of the hydrographic network with the use of paleo-geographical constructions and data on the latest tectonic movements, as has been done in Turkmenistan (Shevchenko (1963).

Groundwater discharge

In natural conditions, groundwater is discharged chiefly via physical evaporation. The role of vegetation transpiration in groundwater discharge is of less significance. Probably, also low is submarine discharge of groundwater to the Arabian/Persian Gulf due to slow lateral underground flow and the presence of low-permeability sediments screening a vertical seepage of artesian waters (Alsharhan et al. 2001). More significant is the ground-

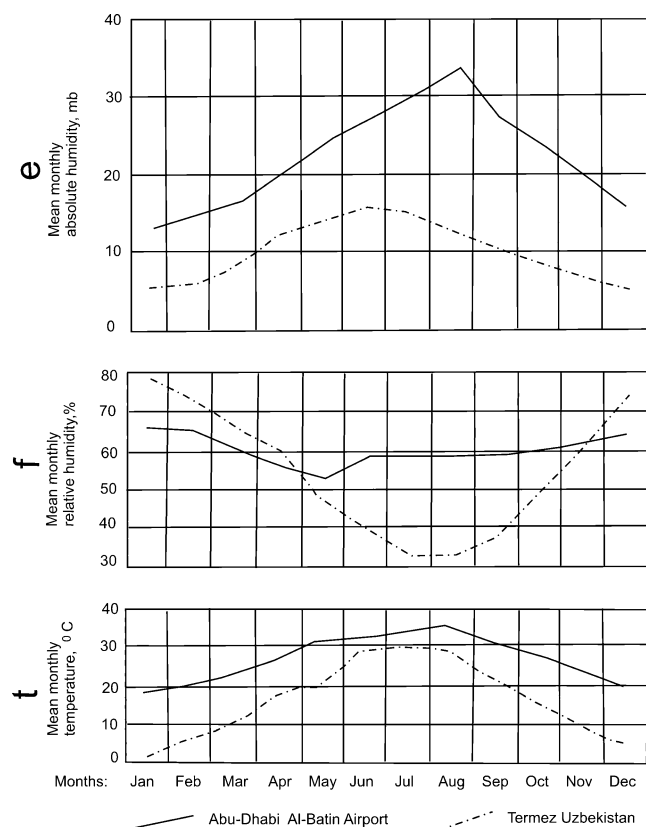


Fig. 6 Average monthly values of absolute humidity (in millibars) and relative humidity, and temperature of air data from the meteorological stations in Al-Batin (UAE) and Termez (southern Uzbekistan; after UAE University 1998 and IHEG 1971–1976, volume XXXIX, Uzbekistan)

water discharge to the Gulf of Oman, to where ground-water flows from the peripheral Quaternary piedmont areas.

Within the literature known to the author, there are no data on the thickness of an active evaporation zone in the northeastern Arabian Peninsula. However, based on research in the dry regions of the former USSR (Ganiev 1979; Kats 1976), including lysimeter investigations, it can be stated that, without vegetation, the evaporation of groundwater sharply decreases with depth. For example, as reported in Ganiev (1979), in the Murgab oasis (Turkmenistan), at a shallow groundwater level of 0.5 m below ground surface (m bgs), the evaporation in the lysimeters with natural vegetation is 940 mm/year, compared to those with bare surfaces where it is 110 mm/year. In the lysimeters with a water level of 3 m bgs, these values are 280 and 20 mm/year, respectively.

Under the conditions of the study region, the decrease in groundwater evaporation with depth should occur more rapidly. The thickness of the zone of active physical evaporation in the northeast of Arabia can be tentatively estimated at not more than 3 m (Dincer et al. 1974).

Evaporation of groundwater also decreases due to the formation of low-permeability evaporite crusts composed of gypsum and carbonates, which are typical of this region. The specific formation of such crusts was identified by Sanford and Wood (2001) on an example of a sabkha in the Abu-Dabi area of the United Arab Emirates. In particular, it was determined by experiment that the basic component in the water balance of a sabkha is precipitation, and the basic component in the salt balance is ascending groundwater discharge from the Tertiary aquifers. The role of lateral water and salt inflow is actually equal to zero. The groundwater evaporation rate depends on precipitation rather than on groundwater inflow, unlike the arid zones of Central Asia and other regions. Even if a correction is made for a decrease in evaporation due to the high mineralization of the groundwater, the evaporation in a sabkha, where the groundwater lies at a depth of between 0.2 and 0.5 m, is still extremely small. The decoded aerocosmic photographs of heat also confirm low evaporation from the sabkha surface. In the southeastern part of the UAE (O.V. Lyashenko, Aerogeologia Company, personal communication, 2001), there are no thermal anomalies in the sabkha, which means that by evaporation rate, the sabkha does not differ from the adjacent areas where groundwater is located at greater depth.

The mechanism of density convection in the system “atmosphere-artesian aquifers” works as follows: in upper aquifers, waters undergo an evaporated concentration, but a part of the concentrated waters are sinking under the action of gravity and mixing with ascending lower-mineralized artesian waters. Thus, closed cycles of groundwater vertical circulation are formed, which slow down the water exchange between the atmosphere and underground hydrosphere. The density convection results in the formation of low-permeability evaporite crusts in sabkhas, which reduces the amount of evaporation. In

order for the mechanism of density convection to work, lateral water exchange must be absent, and this condition is typical of the given region. The absence of biological salt accumulation should be noted.

Based on the experimental determinations of the water and salt balances and analysis of the sabkha formation history for a period of 7,000 years after the sea regression, Sanford and Wood (2001) have shown that littoral sabkhas, are genetically associated not with sea salt penetration, but with discharge of artesian waters. If littoral sabkhas originate at the expense of the discharge of mineralized artesian waters, then it can be considered with certainty that these waters dominate in the formation of inland sabkhas. An important practical conclusion to be drawn from this, is that over a considerable area, sabkhas can serve as the discharge areas of artesian aquifers and, chiefly, of Tertiary aquifers.

As can be seen from the *United Arab Emirates National Atlas* (UAE University 1998), sabkhas (including gypsum accumulations) are widespread not only in the UAE littoral zone, but also along the meridian of 55° east within a belt 30–40 km wide, just where the artesian water regional zone may be located. It can be supposed that within this belt, like in the littoral zone, there is no aquiclude which would prevent the artesian water discharging into the upper aquifers. Thus, the areas occupied by sabkhas, can be considered as indicators of areas with no aquiclude separating an aquifer of Quaternary eolian sands from the Tertiary artesian aquifers. Under such conditions, fossil fresh groundwater, accumulated in the upper aquifers, cannot be preserved for long, as highly mineralized artesian waters will replace it.

Peculiar conditions are typical of the area of Liwa where some fossil waters from the Pleistocene paleo-lake could be preserved under gypsum aquifers, provided that the groundwater within the Quaternary eolian sands is separated by confining beds from the Tertiary aquifers. Thus, taking account of the above characteristics, it would be reasonable to clarify the regional groundwater flow scheme presented in the monograph of Alsharhan et al. (2001). A special focus should be made on distinguishing the areas of aquicludes dividing the Quaternary and Tertiary aquifers. These aquicludes play a key role in the groundwater formation of the given region, as they prevent salinization of fossil waters.

Basic conclusions

1. In the regions of Central Asia, including southern Kazakhstan (arid deserts), and in the northeast of the Arabian Peninsula (super-arid deserts), the basic mechanism in groundwater recharge is the infiltration of surface water runoff, and in discharge, it is evapotranspiration. The predominant sub-type of groundwater formation is allochthonous (i.e. groundwater is recharged not only by precipitation falling in deserts, but also by waters flowing from the mountainous highlands bordering them). Replenishment of groundwa-

ter resources in Central Asia is actively occurring at the present time. In northeastern Arabia the replenishment is low, and the majority of fresh groundwater resources were formed during the previous pluvial epoch. Hydrogeological features of the given regions are mainly determined by zonal-climatic factors.

2. Central Asia is characterized by an active water-exchange in the “mountains–plains” system, which is localized in large drainage basins where regional groundwater flows are formed. A correlative relationship is observed between amounts of river runoff and groundwater replenishment. In the groundwater discharge areas, phyto-hydrogeological systems (ecosystems connected with groundwater) are developed, where transpiration can often exceed 1,000 mm/year. Evaporation becomes more intensive owing to advective penetration of heat into the groundwater discharge zone from surrounding deserts. The thickness of the active groundwater evaporation zones can reach tens of meters. Typical is biological salt-accumulation caused by transpiration of phreatophytes. Vegetation, to a certain degree, controls groundwater recharge at the expense of rainwater infiltration, which is relatively low. Condensation recharge of the groundwater is zero.

Active water-exchange in the upper hydrogeodynamic zone stimulates the formation of clearly expressed horizontal hydrogeochemical zonality, manifested in an increase in water mineralization and in a change in the chemical composition of groundwater with its movement. Up to the upper part of the cross-section (to several hundreds of meters), inverse vertical hydrogeochemical zonality (decrease in groundwater mineralization with depth) is typical. At the same time, active water-exchange in the upper hydrogeodynamic zone impedes the preservation of locally spread fossil groundwater.

3. In the super-arid deserts of northeastern Arabia, water-exchange processes are slow. Groundwater is formed in areas limited by size and width, located directly near the Mountains of Oman. Infiltration recharge of groundwater occurs chiefly in sandy deserts, sometimes in karst rocks. This type of recharge has not been studied in detail but, in quantitative terms, is obviously not great. Lateral groundwater flow is slow. Vapor condensation from the air has a certain importance for groundwater recharge. The absence of or the extremely low productivity of the vegetation determines its slight influence upon groundwater formation. Over the majority of the region, groundwater is discharged via physical evaporation. The thickness of the real evaporation zone is several meters, and evaporation is 10–20 mm/year. Evaporation of groundwater also decreases due to the formation of low-permeability evaporite crusts. In the areas with shallow groundwater, processes of density convection take place, forming, as a result, closed cycles of groundwater vertical circulation that reduce the intensity of groundwater exchange with the atmosphere. Biological salt-accumulation in

the groundwater is extremely low; and because of weak water-exchange, the horizontal hydrogeochemical zonality of groundwater is not observed everywhere. For northeastern Arabia, direct vertical hydrogeochemical zonality is typical, resulting from repeated Cenozoic marine transgressions. The slow water-exchange caused relatively favorable conditions for the preservation of fossil groundwater accumulations, which are often the basic source of drinking water supply.

4. Over considerable parts of the deserts in Central Asia, the hydrogeological conditions are disturbed because of multi-year irrigation. Basic hydrogeological problems lie in the optimization of the usage of surface and groundwater and the minimization of their contamination.

In northeastern Arabia, intensive exploitation of groundwater has been started only in the second half of the twentieth century. The most negative process is the depletion of groundwater resources that are actually non-renewable. Taking this into account, it is necessary to create an optimal water-use system.

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