Clay Translocation in the Artificial Recharge of a Groundwater System in the Southern Zagros Mountains, Iran

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*The shortage of water in Iran and most countries in the arid and semiarid zones is approaching the critical stage. Because about 60% of the water used in Iran is supplied by underground resources and natural recharge cannot replace the amount of water exploited, artificial recharge of groundwater (ARG) is actively pursued in this country. Desiltation of turbid floodwaters in sedimentation basins is a prerequisite for ARG. It is executed close to the heads of alluvial fans on an extensive area in Iran. Because the sediment removal efficiency of sedimentation basins is not 100%, downward migration of some clay particles, both in sedimentation basins and recharge ponds, causes the gradual impermeability and eventual clogging of the vadose zone and reduces the economic life of the recharge systems. Coarse-grained alluvium beneath 2 sedimentation basins, one in operation for 13 years and the other for 11 years, was sampled down to a depth of 7.5 m. Sampling was repeated in a control area outside and adjacent to the ARG system. X-ray diffraction patterns clearly show the presence of illite, chlorite, kaolinite, smectite, and sepiolite. Single laths and bundles of laths of palygorskite–sepiolite, a well-formed 6-sided and a pseudohexagonal flake of kaolinite, and smectite particles with smooth, wavy edges are clearly seen in the transmission electron micrograph. The order of clay mineral accumulation at a depth of 7.5 m was as follows: sepiolite > palygorskite > chlorite. The relatively high concentration of sepiolite may indicate its neoformation in the rooting zone of river red gum (*Eucalyptus camaldulensis *Dehnh.).*

Keywords: *Artificial recharge of groundwater (ARG); clay translocation; groundwater; vadose zone; Zagros Mountains; Iran.*

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وَجَعَلْنَا فِيهَا رَوَاسِيَ شَامِخَاتٍ وَأَسْقَيْنَاكُم مَّاءً فُرَاتًا

"…and set on it [earth] firm mountains reared aloft, and offered you fresh water…"

The Koran: **Morsalat [Those sent]: 27**
Arabic quote by the calligrapher Othman Taha)

Introduction

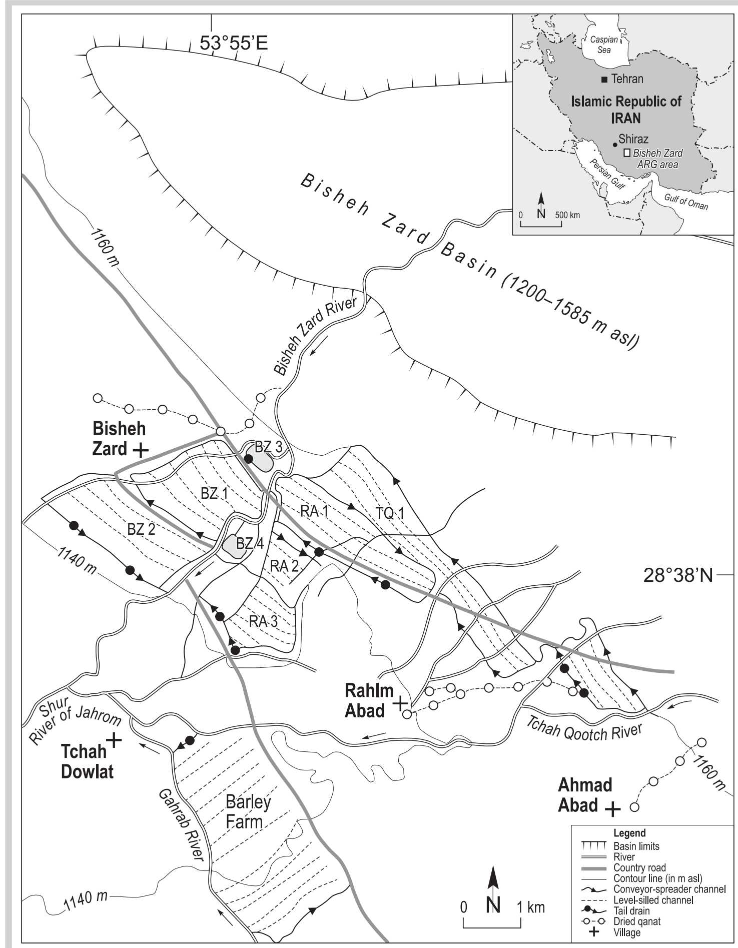
Water shortage is the Achilles' heel that contributes to the break up of civilizations in drylands. The world in general (Postel 1992), and Iran in particular (Kowsar 1998a), is facing a preventable water crisis. Iran is a land of floods, droughts, and *qanats* (underground water collection and conveyance galleries) (Kowsar 1991); groundwater has been the mainstay of life in the Iranian deserts for millennia.

Groundwater supplies about 60% of the water required in Iran during periods with normal precipitation and a higher percentage during droughts. Therefore, survival of humans depends on groundwater resources. Unfortunately, water tables are receding throughout Iran. Rapid population growth and the use of inappropriate technology have contributed to the dramatic situation Iranians are facing today. The arrival of cable tool and rotary drilling machines and powerful pumps was the *coup de grâce* to Iran's groundwater resources. Today, we hope to reverse the trend of receding water tables through aquifer management.

Aquifer management is defined as the art and science of optimizing all resources and methods that bear upon the sustainability of aquifers in one way or another (Kowsar 1998a). The Persians developed aquifer management thousands of years ago. In recent times, the artificial recharge of groundwater (ARG)—the linchpin of aquifer management—has been practiced on a small scale, and pertinent fields of science and technology have been used in designing and implementing recharge systems. This concept today brings into service empty underground reservoirs. Their total capacity is about 5000 km^3. They lie under 410,000 km^2 of coarse-grained alluvium and colluvium. The reservoirs could rapidly be recharged by permanent or ephemeral rivers flowing out of numerous mountain valleys if governmental ARG efforts were increased. The rejuvenation of at least 20,000 *qanats* due to the rise of the water table is an appreciated side effect of ARG in Iran.

Only about 20% of Iran's annual precipitation of 415 km^3 becomes usable surface water or groundwater. This makes effective usage essential. Iran receives an average annual amount of over 52 km^3 of unused floodwater, of which about 42 km^3 is accessible runoff. This is the portion that is realistically available for human consumption (Postel et al 1996). Because most of this flow originates from the watersheds covered by erodible Mesozoic sediments, floodwaters are typically turbid. Because desiltation of floodwater is a prerequisite for ARG, reclamation of colluvial soils, debris cones, and coarse-textured alluvial soils is performed simultaneously if these so-called infertile soils are used as sedimentation basins and recharge ponds in the ARG projects.

FIGURE 1 Sketch map of the Gareh Bygone Plain artificial recharge of groundwater systems. (Map by Andreas Brodbeck)



A very serious drawback of the use of ARG techniques is the increasing impermeability of the recharge area over time. Translocation of fine materials, particularly clay <1 μm, is an ever-present threat to the smooth functioning of the systems. Eventually, clogging of micro- and macropores by illuviated clay may make the entire vadose zone impermeable. As the turbid floodwater infiltrates the soil surface and moves through the vadose zone, foreign matter is separated from the water through 3 distinct mechanisms: particles ranging from 1 to 10 μm in diameter either form a surface mat or are filtered by the topsoil, and particles smaller than 0.1 μm in diameter are translocated by water through the porous media and governed by the physicochemical processes in the soil profile (McDowell-Boyer et al 1986).

The objectives of the study were to:

1. Specifically determine the range of translocation of the clay minerals in the vadose zone.
2. Study the possible transformation of clay minerals in the entirely new environment of an ARG system.

Materials and methods

Study area

In the Gareh Bygone Plain (GBP), the Miocene–Pliocene Agha Jari Formation (AJF) crops out. It consists of calcareous sandstones, siltstones, and marl. Furthermore, the Pleistocene conglomerate with calcareous and cherty cobbles and pebbles (Bakhtyari Formation [BF]) covers the AJF unconformably (James and Wynd 1965). The synclinal upland, formed by the tectonic movements of the Zagros Mountains during the Mio-Pliocene time in the AJF, has made the Bisheh Zard Basin an ideal runoff-producing watershed. The debris cone formed by the Bisheh Zard River emanating from this basin is a good representative of a vast, potential recharge site in southwestern Iran. The alluvium that is derived from these 2 formations (AJF and BF) contains 50–70% cobbles and pebbles. The average slope of the research site is 0.6%.

The GBP is located 200 km to the southeast of Shiraz, Iran (28°35′N, 53°53′E; 1140 m above mean sea level; see Figure 1). Mean annual precipitation and the Class A pan evaporation are 243 and 3200 mm, respectively, based on the records from the Baba Arab Climatological Station, 20 km to the west of the study site (Pooladian and Kowsar 2000). Ten ARG systems, covering 20 km^2 in the GBP, annually capture 10 million m^3 of floodwater. Each ARG system consists of an inundation canal, which diverts floodwater to the head of the first sedimentation basin. A stilling basin, 1–7 km in length, spreads the water as a thin sheet over land. The less turbid water flows into the next sedimentation basin through gaps formed in the bank of a level-silled channel. This process is repeated 3–10 times depending on the turbidity of floodwater. A recharge pond at the end of the system receives the clear water. Because both the basins and pond direct the flow toward aquifers, maintaining their permeability is of utmost importance. More details about the site and its ARG activities can be found elsewhere (Kowsar 1991, 1998a,b).

Sampling

Sampling for clay translocation determination was performed in 3 wells with a diameter of 100 cm dug near the 1140-m contour. Well 1 was dug in the first sedimentation basins of the Bisheh Zard$_1$ (BZ$_1$) ARG system, which has gathered the thickest layer of fresh sediment since its operation began in 1983. Well 2, the control site, was located outside the same system, about 70 m to the north of Well 1. Well 3 was dug in the first sedimentation basin of the BZ$_4$ ARG system, which was forested with river red gum (*Eucalyptus camaldulensis* Dehnh.) in January 1986 (Figure 1).

A steel cage hanging from a steel cable was lowered in each well by a crane. High humidity and the presence of seemingly noxious gases in Well 3 necessitated its ventilation from a depth of 10 m. Soil samples were collected at 1-m intervals to a depth of 7.5 m, except where an obvious change of texture occurred in Well 3. One further sample was taken from the phreatic zone, 50 cm above the water table.

Measurements

Particle size distribution was determined using the hydrometer method (Gee and Bauder 1986). Particle size separation for mineralogical analysis was performed according to the procedures outlined by Kunze and Dixon (1986), with the following modification: $CaCO_3$ removal was attempted by repeated washing with 1 N NaOAc at pH 5 and centrifugation for 10 minutes at 2500 rpm. Cation saturation, glycerol solvation, and clay slurry sedimentation on glass slides were achieved according to Whitting and Allardice (1986).

X-ray diffraction (XRD) patterns were obtained with a Siemens D5000 using $CuK\alpha_1$ radiation and Ni filter at 40 kV, 40 mA, and $\lambda = 0.15418$ nm. A computer-assisted printout of peak intensities was produced by the X-ray system. Specimen preparation for the transmission electron micrograph (TEM) was done according to Kittrick's method (1965). A drop of citrate-dithionite–treated clay suspension was deposited on a Cu microgrid. The TEM studies were performed with a Phillips SM 300 operating at 80 P kV. Mineral identification was achieved according to Bates (1964). Quantities of clay minerals were estimated from their relative peak intensities using the glycerol-treated samples (Johns et al 1954).

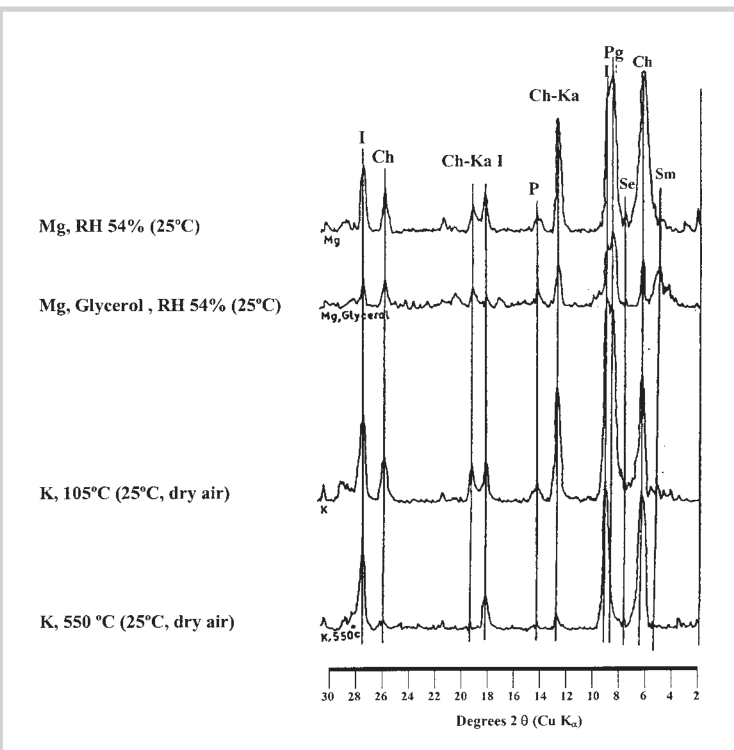


FIGURE 2 XRD patterns for the <2-μm fraction of the treated alluvium from the BZ1. I: Illite; Ch: Chlorite; P: Plagioclase; Pg: Palygorskite; Se: Sepiolite; Sm: Smentite; RH: relative humidity. (XRD patterns prepared by A. Yathrebi)

Results and discussion

The main reason for selecting the sampling sites was that a nearly uniform deposition of the debris flow as well as the bed and suspended loads produced during the Quaternary Period made for nearly identical locations before floodwater spread over them. Therefore, any change in the texture and clay mineralogy could be attributed to the gradual effects of floodwater spreading and, possibly, to the biologically facilitated formation of clay minerals.

Results of the analyses of the <2-mm elements show a nearly uniform particle size distribution from the soil surface to the phreatic zone (Table 1). Moreover, disregarding the sediment deposited on top of the surface soil, the entire profile is loamy sand to sand. Deposition of 90 and 60 cm of medium- to fine-grained particles around Wells 1 and 3, respectively, has changed their surface texture to loam (Kowsar 1998a). XRD patterns of the samples collected to a depth of 7.5 m show the presence of illite, chlorite, kaolinite, smectite, and palygorskite in all samples and the presence of sepiolite only in a few of the samples (Figure 2). The relative abundance of each of these minerals is presented in Table 2.

Huisman and Olsthoorn (1983) have presented the following equation:

$$dp = \frac{dm}{6.46}$$

in which dp is the pore diameter and dm the media diameter. If one takes the minimum silt grain diameter to be 2 μm, because the diameter of a palygorskite lath is 0.02–0.03 μm, it is obvious that this mineral could theoretically pass through a sieve made of the smallest silt grains. Tortuosity is the main deterrent to the smooth translocation of palygorskite–sepiolite laths. The general validity of the equation is suggested by the fact that these 2 minerals were found in higher concentrations in the vadose zone of sedimentation basins than in the same zone of the control areas.

A symmetrical, strong $d(001)$ spacing at about 1.42 nm indicates the presence of chlorite, which is invariant with respect to cation saturation, glycerol solvation, and heating to 550°C for 2 hours. The disappearance of the strong, symmetrical second-, third-, and fourth-order reflections of chlorite after the heat treatment is an

TABLE 1 Particle size distribution of the vadose zone in the Bisheh Zard experimental site. The double line beneath the second row indicates the level of the soil surface. (Source: own data)

Depth (m)	Control			Sedimentation basin without trees			Forested sedimentation basin		
	Sand (%)	Silt (%)	Clay (%)	Sand (%)	Silt (%)	Clay (%)	Sand (%)	Silt (%)	Clay (%)
0.6—0.9	No sedimentation			68	15	17	No sedimentation		
0.0—0.6	No sedimentation			49	29	22	50	23	27
0.0—1.5	82	5	13	84	8	8	73	17	10
1.5—2.5	93	2	5	89	5	6	94	2	4
2.5—3.5	83	9	8	69	12	19	66	18	16
3.5—4.5	94	3	3	77	12	11	75	13	12
4.5—5.5	94	3	3	95	3	2	80	12	8
5.5—6.5	94	2	4	93	4	3	60	22	18
6.5—7.5	94	2	4	92	5	3	91	2	7
Phreatic zone	49	29	22	71	12	17	46	33	21

TABLE 2 Relative peak intensities of Mg-saturated, glycerol-solvated clay minerals at a depth of 7.5 m, in percent. (Source: own data)

Sampling site	Chlorite	Illite	Palygorskite	Smectite	Sepiolite
Control ($Well_2$)	56	79	23	6	4
BZ_1 ($Well_1$)	75	73	37	Trace	11
BZ_4 ($Well_3$)	71	73	38	1	14

indication of its low Fe content. If the mineral had been an iron-rich chlorite, it would have given weak first- and third-order reflections and strong second- and fourth-order reflections (Barnhisel and Bertsch 1989). The first-order reflection was only a little less intense relative to illite after the heat treatment. A shoulder on the low-angle side of the chlorite peak with Mg^{2+} saturation, which expanded to 1.840 nm with glycerol solvation and collapsed to 1.00 nm with K^+ saturation and heating to 550°C for 2 hours, points to the presence of smectite. The collapse of 0.71 and 0.35 nm after a 2-hour heat treatment at 550°C indicates the presence of kaolinite, which was masked by the strong, symmetrical second, third, and fourth orders of chlorite reflection. Two flakes of kaolinite are present in the TEM.

The strong 1.00-nm spacing with Mg^{2+} saturation and glycerol solvation is indicative of illite. The strong reflections at 1.04 and 1.24 nm point to the presence of palygorskite and sepiolite, respectively. Palygorskite–sepiolite fibers are clearly shown in the TEM (Figure 3). The electron micrograph reveals the fibers along with particles that have smooth, wavy edges, which may be indicative of smectite.

Downward translocation of chlorite, palygorskite, and sepiolite is detected in sedimentation basins. Although the BZ_1 sedimentation basin was under operation for a longer period than the BZ_4 basin (13 and 11 years, respectively), the expected greater concentration of palygorskite and sepiolite in the older basin was not found. The presence of abundant root channels in the younger basin, which is planted with gum, provided preferential flow paths that conveyed water and minute clay particles to the lower depths. Furthermore, other biopores, particularly those created by sowbugs (*Hemilepistus shirazi* Schuttz), facilitated such translocations (Rahbar and Kowsar 1997). Surprisingly, we observed palygorskite in the samples (Figure 3). Mirnia and Kowsar (2000) could not detect this clay mineral in the XRD patterns, and only a few strands were shown in a TEM. Therefore, it seems that this very small clay mineral carried in suspension should exist in such a concentration to be detectable by X-ray. In addition to the single laths and bundles of laths of palygorskite–sepiolite, a well-formed 6-sided and a pseudohexagonal flake of kaolinite as well as smectite particles with smooth, wavy edges are clearly seen in the TEM.

The reason for the presence of palygorskite in the phreatic zone of the control well may be its translocation through the flow of water over 30 years in a *qanat* at a depth of 8 m, 50 m upstream of the well. Apparent-

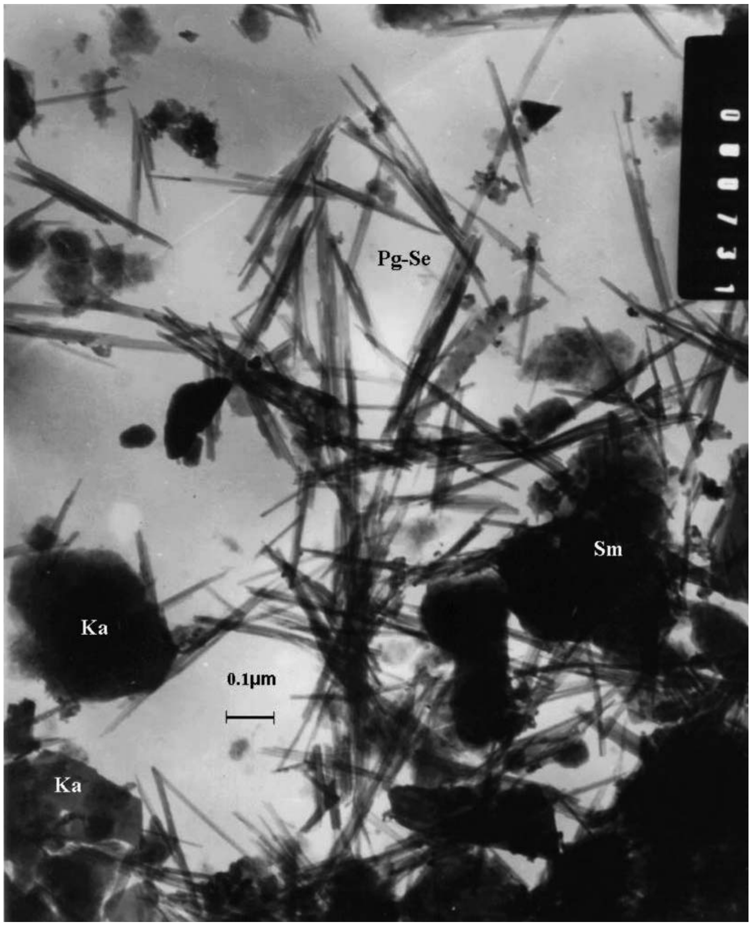


FIGURE 3 Transmission electron micrograph (TEM) of palygorskite–sepiolite fibers in a sediment–clay assemblage with kaolinite, smectite, and other minerals in a sample taken at a depth of 7.5 m in the forested site. (TEM prepared by A. Adeli)

ly, the flow that emanated from the watershed contained small amounts of palygorskite, which—by seepage and subsequent deposition in the vadose zone—was concentrated at a depth of 23 m in the area where the control well was dug. The question of the possibility that smectite was altered into palygorskite might arise. Abtahi (1977) has proposed this process under saline and alkaline conditions in Iranian soils. However, the soil and floodwater of the experimental site are nonsaline and nonsodic (electrical conductivity of soil = 0.5 ds/m, pH of soil is 7.9; electrical conductivity of floodwater = 0.3 ds/m, pH of floodwater is 7.5). Furthermore, alteration of smectite into palygorskite is not very likely because of the significant energy requirements for the breaking of bonds involved in the inversion of tetrahedra (Singer 1989). However, a drastic decrease in the concentration of smectite does not permit total dismissal of this formation mechanism.

A particular species of termite has been credited with the formation of smectite from mica (Robert and Berthelin 1986). The seedlings of white cedar, hemlock, white pine, white spruce, red oak, and hard maple form kaolinite from biotite (Spyridakis et al 1967). Therefore, it is possible that some micro- or macroorganisms (or both) such as sowbugs and eucalyptus roots might have been instrumental in sepiolite formation; this requires a thorough study.

Because sepiolite laths are thicker than palygorskite laths, their translocation in the vadose zone should be hindered more than the translocation of palygorskite. Because the ratios of the percentages of these 2 clay minerals at a depth of 7.5 m between BZ_4 and the control area are 1.6 for palygorskite and 3.5 for sepiolite, it becomes apparent that other mechanisms might have been involved in this process. Biogeochemical transformation is a possibility that has to be verified by further research.

Conclusions

The increase in the concentration of sepiolite, palygorskite, and chlorite at a depth of 7.5 m proves that we were rightly concerned about the eventual impermeabilization of the vadose zone by the translocation of extremely small particles. The relative abundance of these minerals in comparison with the control area is 3.5 for sepiolite, 1.6 for palygorskite, and 1.3 for chlorite. As sepiolite fibers are thicker than palygorskite fibers, they should have been filtered more readily than palygorskite. Therefore, neoformation of this clay mineral may be involved. This requires further study.

Floodwater spreading in a dry desert increases soil water content. This in turn influences consequent mineral weathering and biogeochemical processes and subsequent alteration or neoformation (or both) of minerals such as sepiolite.

Practical implications

Finding economical ways and means of coagulating clay minerals <1 μm in diameter, particularly sepiolite and palygorskite, may prove logical in the long run. Addition of coagulating agents that do not adversely affect water quality may prove advantageous in lengthening the life of sedimentation basins.

Because permeability of the forested sedimentation basins has not changed perceptibly in 17 years of operation, afforestation of such basins is recommended. Because river red gum is a prodigious water consumer, the optimum stocking rate has to be found to strike a balance between the desired root channel distribution and the volume of water that has to be consumed to have them functioning. Selection of more suitable trees to replace the red river gum is underway through species trial.

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