Arab J Geosci (2016) 9: 47
DOI 10.1007/s12517-015-2076-0

ORIGINAL PAPER

# Hydropedology and soil evolution in explaining the hydrological properties of recharge dams in arid zone environments

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Received: 11 January 2015 / Accepted: 10 September 2015 /

**Abstract** The effects of anthropogenic activities on soil evolution due to siltation and the impact on hydraulic properties of the vadose zone on the augmentation of the aquifer recharge are investigated for the Al-Khoud dam in Oman. Inside the dam reservoir and in areas adjacent to the embankment, downstream, 33 pedons (of depths between 1.5 and 2 m) were excavated and studied during 2011 and 2012. Soil analysis revealed that the subsoil's physiochemical properties of the study area are continuously changing due to damming, i.e., alteration of the natural runoff, intensified sedimentation, and infiltration. Variation of hydropedological properties caused by the geotechnical construction is evident in a distinct vertical stratification of texture of accrued sediments and almost an order of magnitude drop in saturated hydraulic conductivity ($K_s$) of the dam bed. Correspondingly, spilling of ponded water over the dam crest occurs more frequent and therefore increases the potential hazards of flooding of the downstream recharge area. Some fine particles of the suspended load carried to the reservoir by the feeding wadi migrate vertically downward, driven by seepage, into the originally coarse matrix of the parent soil and cause clogging of large pores (with time, hard pans in the subsurface are developing) even without visible cake formation on the soil surface. Development of hard pans was also discovered in pedons at depths close to 1 m. This is attributed to presence of a pedogenic carbonate derived from the parent rock and formed by precipitation of dissolved salts due to a vertical upward moisture evaporation to a hot and dry bed surface during prevailing dry bed periods of dam operation. $K_s$ measured downstream of the dam was relatively high (6 m/day) and was three times higher than the average value inside the reservoir (2.1 m/day), ranging there between 0.01 and 3.96 m/day, but less than at the upstream site outside the reservoir.

**Keywords** Soil evolution · Sedimentation · Recharge dam · Infiltration · Hydraulic conductivity

## Introduction

In arid zones (like Oman), recharge dams are one of the effective measures to replenish groundwater systems by intercepting flash flood water for the purpose of enhancing recharge (Ministry of Regional Municipalities and Water Resources (MRMWR) 2010; Abdulrazzak 1997). Unfortunately, the runoff water carried by dam-feeding wadis is rich of suspended solid materials, with the sediment yield in Oman exceeding 678 t/km$^2$/year (MRMWR 2010). Commonly, a detained sediment-rich flash flood is kept in the dam reservoir for about 2–3 weeks, during which a Stocksian settlement of suspended particles takes place. This

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results in siltation of the reservoir bed. Siltation is deposition/accumulation of fine soil particles carried by runoff water to the dam reservoir (lake). After detention, the relatively clear ponded water is released through culverts (sluice gates) to the recharge basin downstream the dam (Fig. 1).

Studies showed that the efficiency of recharge dams drops with time due to siltation (Biswas 1996; Sichingabula 1997; Alessandro 1998; Chanson and James 1998; Wanyoni 2002; Haimerl 2002; Devi et al. 2007). Chanson and James (1998) reported that accumulation of fine soil sediments in dam reservoirs is a major problem as it reduces water storage capacity and thereafter shortening the dam lifetime and increasing the maintenance cost. The dam scaling problem also reduces the attenuation of the flood and may increase the over-flow (Devi et al. 2007; Joseph 1953). Along with scaling and caking problems caused by siltation, changes in the hydrological properties (e.g., decrease in infiltration) of the original soil is common (Al-Muttair et al. 1994; Kacimov et al. 2010; Al-Ismaily et al. 2013; Prathapar and Bawain 2014; Al-Ismaily et al. 2015). Studies showed that the decrease in the infiltration rate of dam's reservoirs may cause a frequent spilling of ponded water over the dam crest (Haimerl 2002; Joseph 1953; Devi et al. 2007).

To combat or bypass the silt cake layer at the surface of the reservoir bed, scraping is practiced to improve both storage capacity of the dam and infiltration to some extent. Although scraping of the cake is costly, taking into account the periodic flooding and new doses of silt after each flood event, it does not completely solve the problem, especially with the reduced hydraulic conductivity of the dam bed. We hypothesize that part of the fine soil particles would migrate deep into the subsurface vadose zone resulting in alteration of its hydrological properties.

The Al-Khoud recharge dam is one of the largest recharge dams in Oman that experiences a siltation problem like many other dams around the world. Infiltration inside recharge dams (as the Al-Khoud dam) is not considered as the main function of the dam, as the groundwater recharging is taking place in zones downstream of the dam. The dam bed is considered as a generic soil massif subject to rapid hydropedogenic processes that cause easily observable and well-recorded changes in soil's physical, chemical, and morphological properties due to human (geotechnical) interference into the natural system, i.e., wadi flow and original parent soil. It is also essential to develop a way on how to utilize efficiently the huge quantity of incoming flash floods through allowing relatively quick water infiltration that will minimize water losses through evaporation of retained water along with enhancing replenishment of aquifer underneath. Moreover, as to the problem of land availability and the high economical value of the land adjacent to recharge basin, urbanization takes place. This results in shrinkage of the originally designed recharge area downstream of the dam. As a consequence, recharge efficiency will be affected as well as the flooding hazards will increase due to more concentrated runoff.

Understanding the interplay between pedology and hydrology assists in better explanations of both soils genesis/evolution and water dynamics in surface and subsurface systems (Lin 2003; Bryant et al. 2006). Water is an important climatic soil formation factor that plays role in processes such

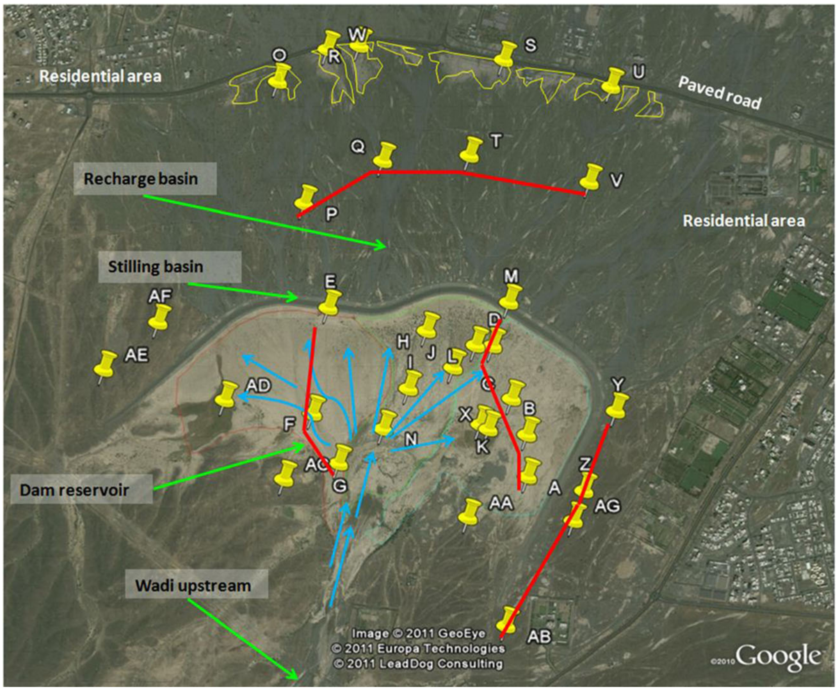


**Fig. 1** Al-Khoud recharge dam with pedons' locations (*yellow pins*); designated transects of selected pedons are marked as *red lines*, and *blue arrows* are water paths in the wadi branches during flash floods (satellite image taken from Google Maps, 2010)

as transportation, deposition, and translocation of the eroded and dissolved materials, which morph the soil. Similarly, understanding the soil properties is also important—and has been widely studied in the literature—as they control the water dynamics, patterns, and distribution of water in porous media, especially flow through the vadose zone (Bell and Cameron 1906; Watson et al. 1995; Schoelkopf et al. 2000; Stange et al. 2003). Human intervention (as buildup of recharge dams) allegedly accelerates the hydropedological processes in the original soil and progressively diminishes the value of the structure itself (Bella and Overton 1971; Peavy et al. 1985; Dalal-Clayton and Sadler 1999; George 2000; Lin 2003; Hari and Krishna 2004; Mohamed 2004; Pahl-Wost 2006). Examples of altered properties include soil texture, structure, mineralogical composition, and hydraulic properties of wadis (natural water transporting channels), flood plains, and basins.

The main objective of the present study is to explore the effects of anthropogenic (geotechnical) activities on the subsurface soil properties of the Al-Khoud recharge dam and the consequent impacts on soil hydraulic properties which are important for the augmentation of water resources of the underlying aquifers.

## Description of the study area

Al-Khoud dam, built in 1985, is located 50 km northwest of Muscat near Seeb town and positioned between 23° 36.9′ and 23° 38.8′ N latitude and between 58° 10.2′ and 58° 09.6′ E longitude (Fig. 1). The dam is placed in wadi Al-Khoud alluvial fan based on recommendations by previous studies (Stanley Consultants 1981). Wadi Al-Khoud is the drainage channel of Samail catchment with an area of 1635 km$^2$ (MRMWR 2008). The dam has a crest length of 5100 m and intercept wall height of up to 11 m with reservoir area of 3.2 km$^2$ (Al-Ismaily et al. 2013). The highest part of the Al-Hajar mountain range drained by the Samail catchment is built up of rocks belonging to the Hajar unit, as well as the Oman ophiolite nappes and interlayered limestone which provide the catchment with gravel and sediments making the Al-Khoud alluvium formation (Al-Ghafri 1991; Al-Rawas et al. 1998). The original soil of the study area is very gravelly and sandy in texture, mostly dominated by Calcids, Gypsides, and Orthents (MAF 1990; Al-Ismaily et al. 2013; Al-Ismaily et al. 2013). Al-Khoud dam is mostly dry during the year, with infrequent short-duration highly intensive precipitation received. During the last few years, over-spilling of ponded water occurred three times during two major cyclones' outbreak which struck Oman in 2007 and 2010 (Kacimov et al. 2010; Abdalla and Al-Abri 2011; Al-Ismaily et al. 2013; Al-Ismaily et al. 2015) and during the occasionally heavy rain events in 2013 (Al-Saqri 2014).

## Research methodology

A reconnaissance survey with a set of field and laboratory experiments was conducted to study the soil properties of the area. With the aid of satellite images using Google Earth©, the site selection for the excavation of pedons was based on the heterogeneity in the morphology of the topsoil features such as color and texture, variation in the microtopography, pathways of the runoff network, and patterns of vegetation. Out of 33 excavated pedons, 15 were inside the dam reservoir and 18 outside the dam. Figure 1 illustrates the distribution of the soil pedons, which are marked and labeled with uppercase alphabetical letters. Among the 18 "external" pedons, 12 pedons are in the recharge basin and the other 6 are in the upstream area sufficiently far from the reservoir when it is full of water (i.e., beyond the backwater curve) or laterally behind the embankment and never flooded by the reservoir water. In other words, the "upstream area" is a benchmark against which the reservoir bed is compared. This "reference area" does not mean that soils (sediments) there are static. This area is not affected directly by the dam constructed in 1985.

A total of 270 soil samples were collected from each soil horizon based on their distinctive pedogenic features. Several transects of logically based selective pedons were designated to reconstruct the soil subsurface morphology and textural variations in a quasi-3-D manner (indicated in red lines in Fig. 1). Percentages of the soil separates (sand, silt, and clay) were determined using the hydrometer method (Gee and Bauder 1986). The different sand fractions were also measured (Tan 1996). Extract soil solutions were prepared using the standard procedure suggested by Tan (1996) and were analyzed for the following: pH$_e$, EC$_e$ (by *DiST4-HANNA* and *Jenway*), and exchangeable cations (by inductively coupled plasma (ICP); Montaser and Golightly 1992). The micromorphology of the soil fabric was examined using scanning electron microscopy (SEM by *JEOL JSM-7600 F*) technique and described according to Brewer (1976) and FitzPatrick (1993).

Saturated hydraulic conductivity ($K_s$) was determined using tension infiltrometers (Reynolds and Elrick 1991) at sites adjacent to some of the selected pedons. In coarse soils at the beginning of infiltration from a ponded soil surface into a dry subsurface, the velocity of water particles is so high that the upper limit of applicability of the Darcy law is exceeded, as discussed in details in Polubarinova-Kochina (1977). However, more general laws will require additional physical constants, which will make the infiltration test in the standard protocols hardly applicable. Thus, the deviation from the Darcy law and the corresponding errors are ignored.

For this study, $K_s$ is of main interest, whereas the sorptive number is not, because in conditions of heavy (several meters in depth) ponding of the reservoir surface for days-weeks, capillarity is of less importance in infiltration. Total suspended solids (TSSs) of the runoff water were measured during a rainfall event that occurred between 28 April and 8 May 2013. Total dissolved solids (TDSs) were also measured for samples collected from different locations, the upstream zone (2 km upstream the dam), at the dam, stilling basin, and recharge area.

We recall that TDSs are defined as concentration of solutes (ions and molecules) in water as solvent; TSS is the concentration of relatively large solid particles which settle in water gravitationally. TSS in fluvial sedimentology consists of both suspended and bed load. The former consists of fine particles continuously supported by the current without contact with the channel bed. The latter consists of larger size particles, which are carried by the current in contact with the channel bottom (see, e.g., Shahin 2007).

## Results and discussion

### Suspended and dissolved solids in the flash flood water

The amount of sediments arriving at the reservoir is a function of discharge of the feeding wadi, secondary soil erosion of the wadi-reservoir bed, nature of the parent's rock/sediments, and the flood plain zones associated with each particular flood (Wanyoni 2002; Devi et al. 2007). When the suspended solids reach the reservoir, the amount of fine sediments deposited on its bed varies based on the topographical features, local surface hydrology of the turbid water, and deposition patterns that eventually result in soil layering-caking (Kacimov et al. 2010). This was clearly observed and measured in the areas where topographical depressions act as water detention compartments and, correspondingly, "sinks" receiving higher amount of deposited sediments. The cake thickness reaches up to 3 m in some areas (e.g., 40 cm near pedon N and 2 m at the site of pedon AD; Fig. 1).

In this study, the suspended load and bed load were quantified as TSS and depth of sediments on the top of the parent soil, respectively. In most studies of wadi channels, the "sediment load"—measured as mass basis per unit volume—is the most significant quantitative parameter, due to the fact that non-cohesive fine sediments (like fine sand and silt) have a low shear stress (Reid and Frostick 1994; Wanyonyi 2002). Figure 2a shows the TSS concentrations for the different locations including upstream, dam reservoir, stilling basin, and recharge basin downstream (see Fig. 1).

In the wadi upstream, a higher amount of suspended solids was transported with concentrations reaching up to 41 mg/L (Fig. 2a). The TSS reduced four times when the flash flood water was detained by the dam. Obviously, as flow velocity decreases, the ability of the current to carry sediments also decreases, and hence, the sediment load begins to deposit (Wanyonyi 2002). Surprisingly, the TSS concentrations in the stilling basin of the dam and in the recharge zone downstream were almost similar to the wadi upstream (e.g., on 3 May 2013, we measured 44 mg/L downstream corresponding to 41 mg/L upstream). This could be attributed to the over-spilling and sluice-gate discharging of the sediment-rich ponded water to the stilling basin. From there, this water flows to the recharge area. The over-spilling flow, along with the culvert-passed turbulent discharge, re-mobilizes, after each flood event, the previously accumulated sediments back into suspension. Part of these suspended sediments settles in areas close to the spillway (see Fig. 3a), while others easily reach the recharge basin and may gradually change the physical properties of the subsurface soil when migrate vertically with seeping water.

The TDS values at the sampling points across the upstream zone toward the recharge basin ranged between 200 and 740 mg/L (Fig. 2b). In general, the upstream loci had higher TDS values compared to the sampling points of the dam reservoir, and thereafter, dynamically, TDS of water in the reservoir is relatively low straight after the rainfall because the first input into the dam storage comes from the runoff and residence time of water particles which enter the dry dam is small. With time, the wadi brings more water which was in contact with the minerals, both the wadi bed and the subsurface. Therefore, TDS of water in the dam is less than that in the feeding wadi because the originally fresh major volume of stored water gets only slightly concentrated by a continuously added wadi influent.

We realize that a single-flash flood data are insufficient as potentially biased. Unfortunately, the wadi is not sedimentologically gauged and continuous TDS-TSS measurements are needed for better understanding of relation between the hydraulic characteristics of a flood event and sedimentation pattern.

### Reduction in the storage capacity of the dam

The reduction of the dam storage volume due to siltation indirectly reduces the flood attenuation with even more over-spilling of ponded water to the downstream recharge basin (Chanson and James 1998). The change in dam's storage capacity was calculated and estimated as the total volume reduced per unit width of the dam crest. Figure 4 (not up to scale) shows a schematic diagram of a cross-sectional area. The volume of the accumulated sediments for transect 1 (representative of all inside dam's transects shown by Fig. 1) was estimated and found to be 708 $m^2$ per unit width perpendicular to the plane of Fig. 4. The original designed storage capacity volume of the dam is 2275 $m^2$ per unit width. Based on these calculations, it was estimated that more than 30 % of the dam storage capacity was reduced since the dam construction, 30 years ago. From this assessment, we surmise that the total

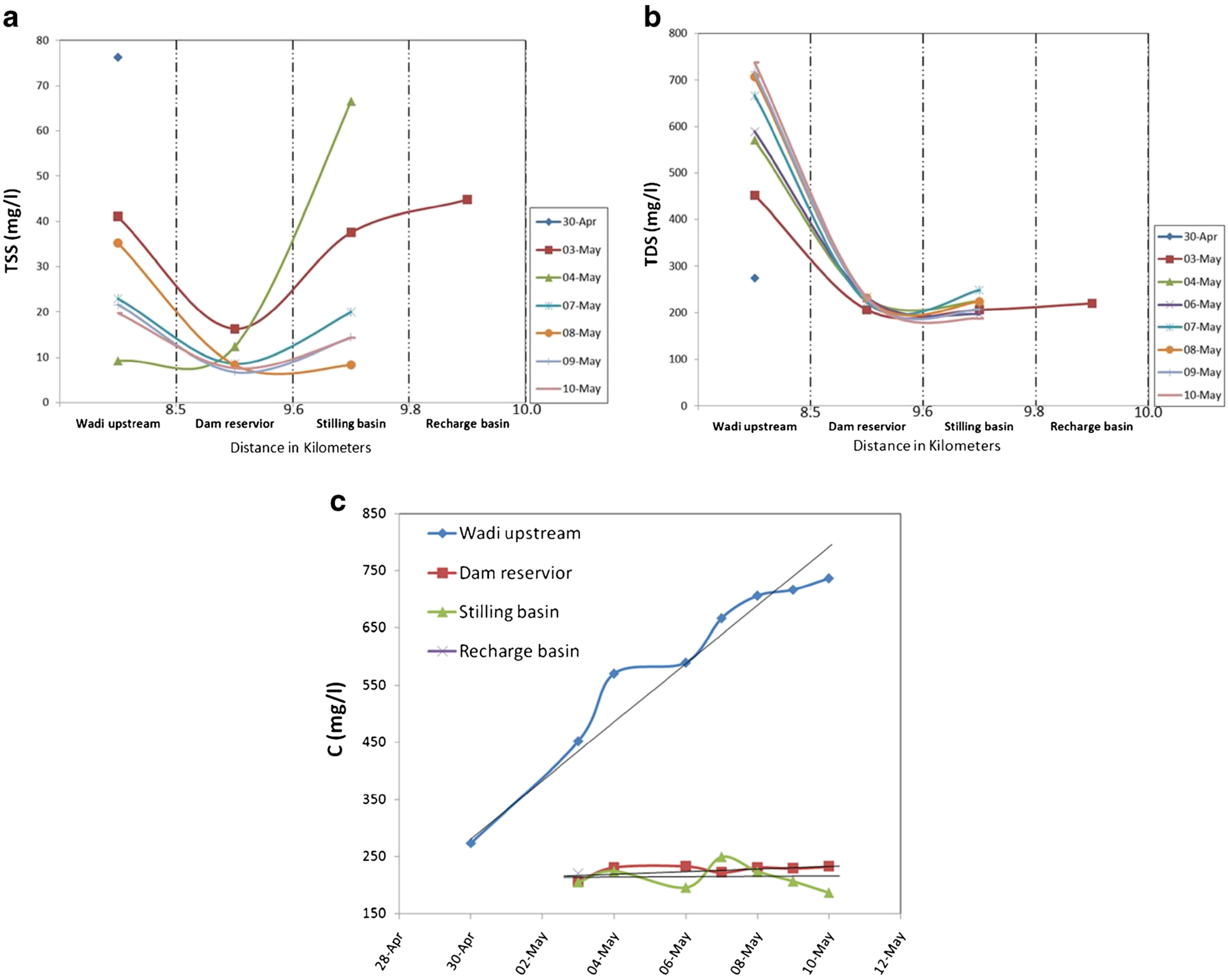


**Fig. 2** **a** Total suspended solids (TSSs), **b** total dissolved solids (TDSs) for different locations at the study area, and **c** TDS concentrations as functions of time at different sampling points

volume of the reservoir is now 7.9 Mm$^3$, compared to 11.6 Mm$^3$ as the originally designed capacity (Stanley 1981; MRMWR 2010). This estimation does not account for local depressions of the lake bed surface.

Historical data (from 1982 to 2012) of the total discharge volume and hydrographs of flood water intercepted by the dam were recorded by the stream gauging station that is located 8.5 km upstream from the dam reservoir (Figs. 1 and 5a). The hydrograph is used to estimate the volumes of water spilled over the dam crest (Fig. 5b, c). From the hydrograph, we see that since the construction of the dam in 1985, three extreme rainfall events occurred (storm—March 1997, Gonu cyclone—June 2007, and Phet cyclone—June 2010), during which the dam was over-topped (Fig. 5b). As the designed dam storage capacity of 11.6 Mm$^3$/day, and the estimated 30 % reduction in storage capacity, the over-spilling to the stilling basin becomes more frequent (over-spilling occurred five times for the years from 1985 to 2012; Fig. 5b).

## Textural analysis of the subsurface soil

Figure 6 presents soil textural distribution with depth for selected soil pedons as representative for the indicated soil layering patterns (those are pedons A, B, C, G, I, J, L, M, and X). These layering patterns could be characterized by (1) accumulation of thick (20 to 40 cm) silt cake layers on the top as in Fig. 6a, (2) stratification that indicates Stokes' settlement after each major/different flash flood events in Fig. 6b, and (3) possible vertical translocation of silt/very fine sand down through the original parent soils as in Fig. 6c. This mobility and translocation of the silt/very fine sand-laden suspension is attributed to the several days to weeks of high water ponding of ≈10 m, after each major flood, and to the filtering/detention of these moving downward fine particles by the coarse parent soil (Fig. 7; Al-Ismaily et al. 2015; Prathapar and Bawain 2014; Faber 2013).

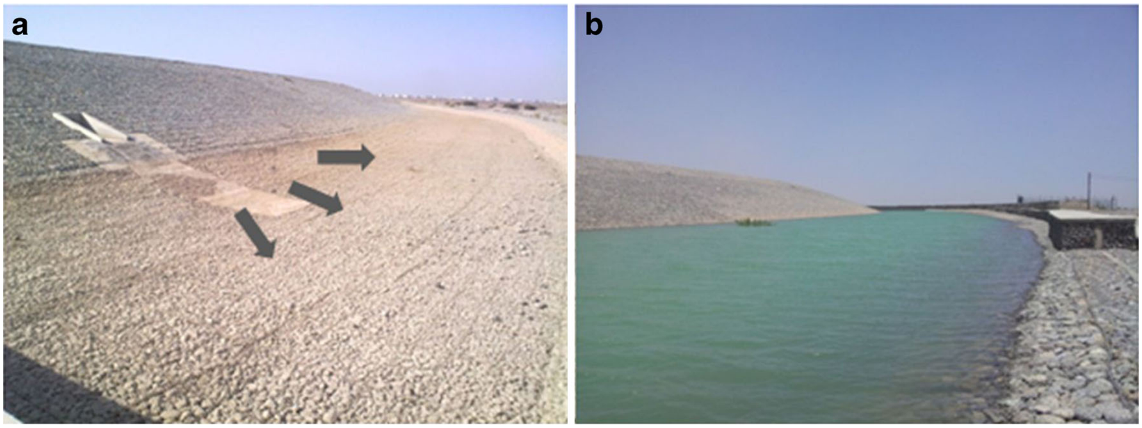


**Fig. 3** **a** Dry dam slope in the spillway section for the embankment, with a distinct "light-color" band previously accumulated fine sediments deposited from the last flood when the stilling basin was full of water. **b** Stilling basin few days after opening of the dam culverts

Based on field observations of the soil profiles, the subsurface structure for the soil skeletal of the parent soil inside the dam appeared to be plastered with the "pulses" of the migrated fine particles, as compared to outside the reservoir area where the parent soil still preserves its loose sand and gravelly structure (Fig. 8a, b, respectively). In addition, the horizon boundaries of several soil profiles revealed the occurrence of a sharp textural discontinuity, i.e., abrupt transition from a layer with a coarse to fine texture or vice versa, besides to what we call "structural discontinuity" caused by the plastering. Such discontinuities, i.e., changes in texture and/or structure, were common in soils inside the reservoir bed. With soils of the recharge area, the over-spilling of the sediment-rich ponded water has also created textural discontinuity in the form of thin surface caking that overlies the coarse parent soil (Fig. 9).

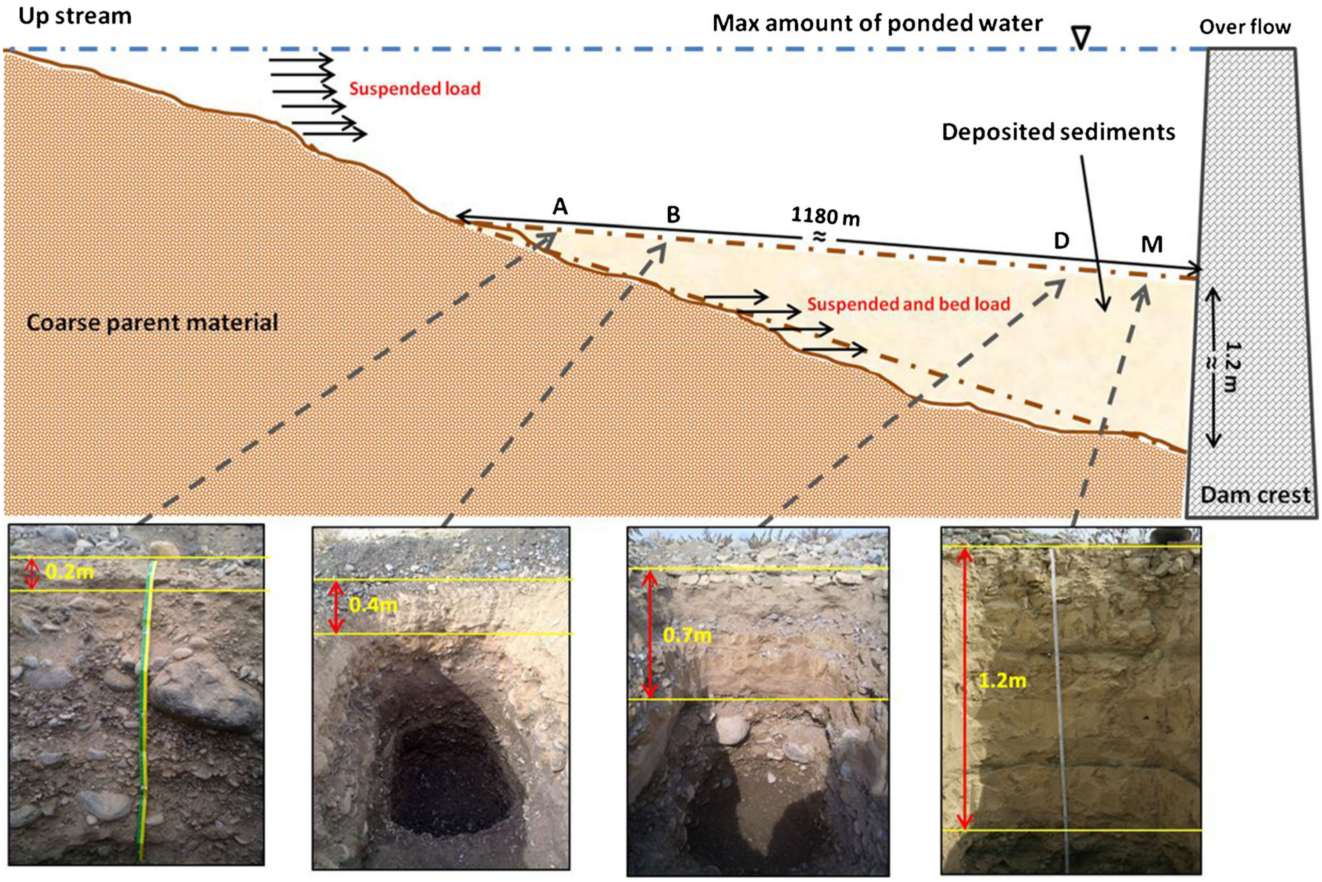


**Fig. 4** Schematic diagram (not up to scale) of a cross-sectional area of deposited sediments in the reservoir basin of the dam with photos of pedons along the transect

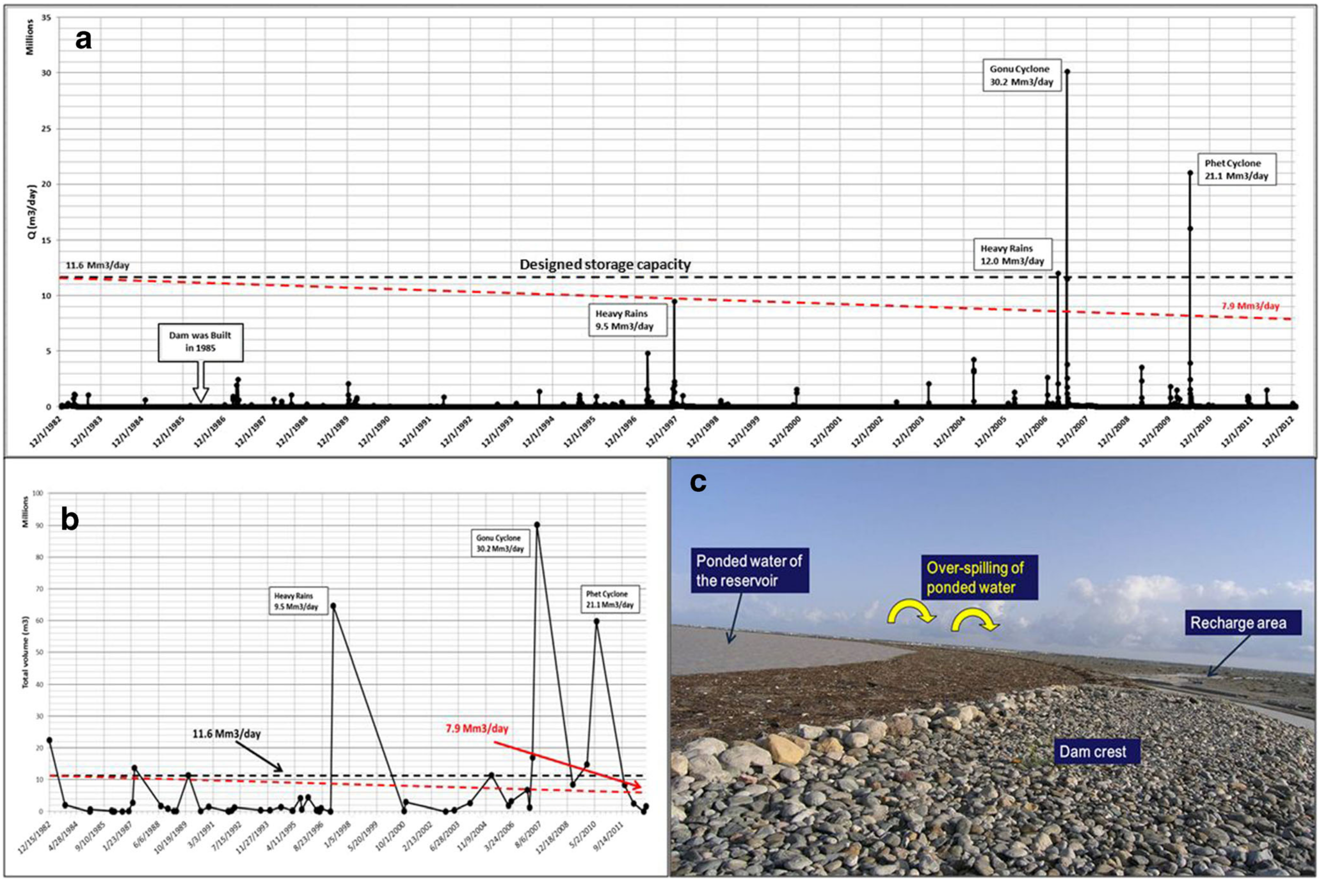


**Fig. 5** **a** Dec. 1982 to Dec. 2012 daily discharge measured by the Al-Khoud gauging station upstream of the dam. **b** Total volumes per day of water received after each major raining event. **c** Over-spilling of ponded water through the stilling basin to the recharge basin of the study area for the rainfall event of 28 April to 3 May 2013

For a close inspection on the effect of plastering on the micromorphology of the soil fabric, several soil clods were collected from the parent soils, which are over-topped with surface caking, i.e., at the transition zones just below the deposited fine sediments. Similarly, the clods were sampled from zones without any caking on the top. The SEM photomicrographs revealed a denser soil fabric with a higher coated matrix of the soil clods collected from zones that are over-topped with surface caking compared to the matrix of the clods that represents the original soil porous media (Fig. 10a–d, respectively). With samples of a denser fabric (Fig. 10a, b), the sand grains are randomly packed with bridges of finer materials which appeared to fill the soil voids.

The occurrence of discontinuities may impact pedogenic processes such as translocation, i.e., the illuviation and eluviation processes, and transformation. Discontinuities where a fine material overlies coarse layers increase the hydraulic tensions and "hanging" of the percolating water in the upper fine-textured materials (so-called capillary barrier phenomenon). This leads to less frequent wetting of the coarse materials below and more chance for the illuviated material to be deposited at the contact zones (Schaetzl and Anderson 2005; Khakural et al. 1993). In our case and based on profile descriptions, there was an incipient accumulation of calcic materials in zones where discontinuities occur, primarily on the undersides of pebbles and gravels (Fig. 11). Carbonate-rich water appears to persist there, and when it later evaporates, especially during summertime and when the topsoil temperature reaches up to 70 °C, desiccation occurs and carbonates precipitate. We speculate that these are secondary carbonates at their stage 1 of development as based on the *per descensum* model, which relies heavily on input of carbonates "descending" into the soil via percolating water and the morphologies of $CaCO_3$ accumulation (Treadwell-Steitz and McFadden 1999; Alonso-Zarza et al. 1998).

Similar to a natural sand filter, the reservoir bed causes retention of large-sized particulate sediments and allows particles with average sizes smaller than the pore size of the soil to pass through until the particles are trapped by the matrix (De Zwart 2007; Siriwardene et al. 2007; Faber 2013). The recharge bed downstream the dam continuously receives (after each major flood event; Fig. 5c) pulses of sediment-rich water over-spilled (as explained earlier). Part of these

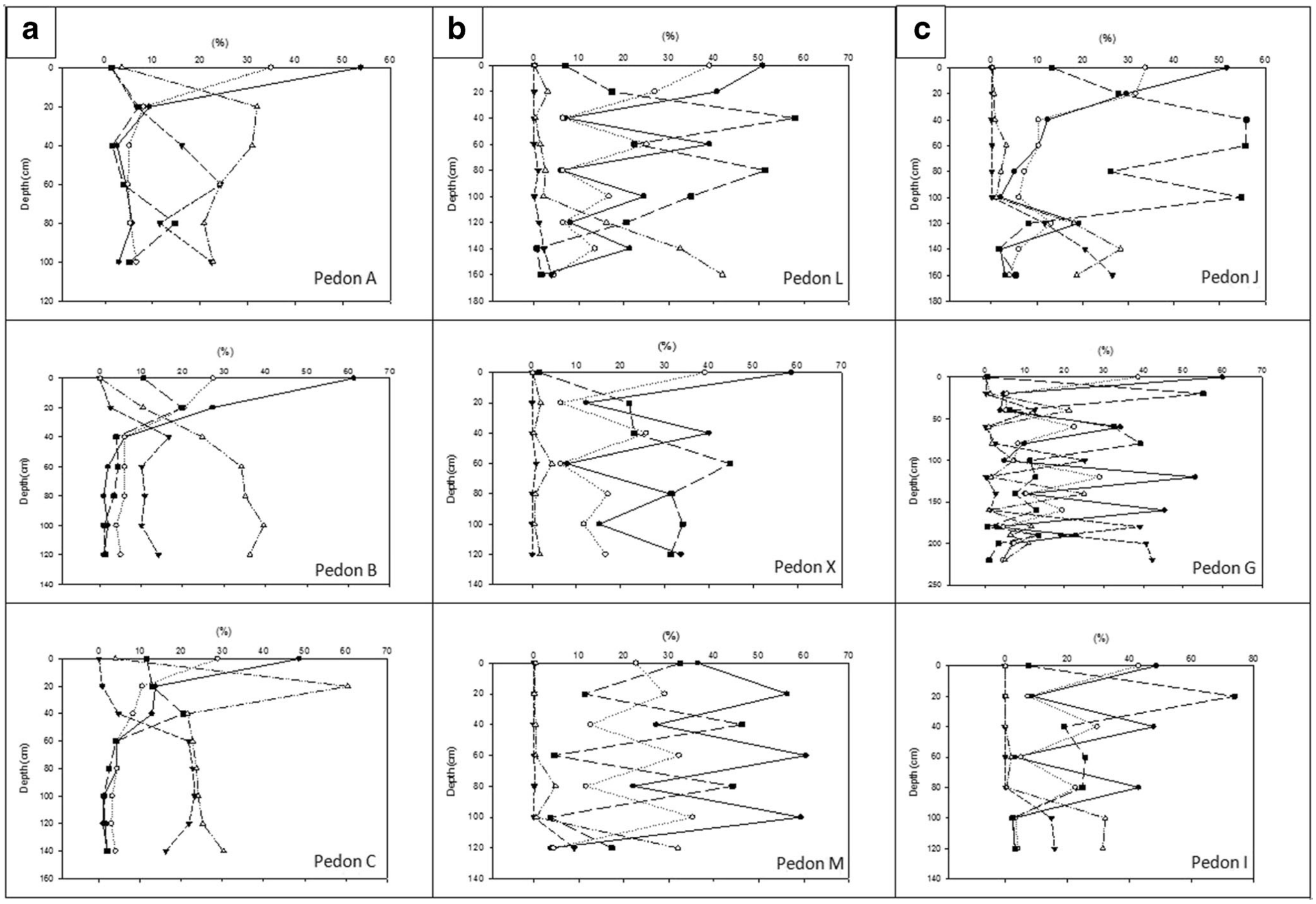


**Fig. 6** **a** Normal accumulation of silt on top of original soil. **b** Stratified layer of sediment soil after each flooding event. **c** Sedimentation on top surface and accumulation of silt at lower depth (*some data modified from* Al-Saqri 2014)

sediments would migrate deep into the subsurface or start to accumulate on the soil surface. The dynamics of these moving particles is complex. Fine particles attach to the sand particles while seeping, and detached particles move further down. The process of attachment and detachment will occur due to the ponding hydraulic gradient on the top that pushes particles further down until they are trapped in the narrow openings as shown in Fig. 10b (Al-Saqri et al. 2013; De Zwart 2007; Faber 2013). The particles accumulate with time and result in a dense blockage of the pores more in the top than lower layers as in Fig. 10a compared to that presented by Fig. 10b.

The intricate relationship between infiltration and mobilization of fine soil particles within the coarse filter material deserves more attention as these migrated particles may adversely affect the subsurface hydrological properties (e.g., reducing the infiltration rate), even when the silt cake is scrapped (as it is the practice in Al-Khoud recharge dam). Understanding complicated soil heterogeneity patterns of the subsurface is of vital importance for better understanding the dynamics of subsurface water within the vicinity of recharge dam which is extremely important for the mitigation of problems with water resources in Oman.

## Hydraulic properties

Soil permeability across the study area was quantified at different sites inside the reservoir bed and outside in the recharge basin using disk tension infiltrometer (Wooding 1968; Reynolds and Elrick 1991). $K_s$ measurements are listed in Table 1 for areas adjacent to the selected pedons presented by Fig. 1. Although the double-ring infiltrometer and the tension infiltrometer techniques give different values of $K_s$ and capillary properties of the soil (wetting front pressure and sorptive number, respectively), the usage of the latter method was motivated by the planned agroengineering applications of the very top silt layer of the dam bed. Moreover, the tension infiltrometer disk is small enough to be fit between the major cracks of the top sediment layer, while a standard double infiltrometer ring has too large diameter to avoid the cracks.

Area close to pedon AG which represents the original soil before dam construction that is not subjected to flooding is relatively of high conductivity ($K_s$=7.30 m/day). The measurement corresponds to that Stanley Consultants in 1981 prior to dam construction. The hydraulic conductivity of the relatively un-silted soil at the upstream part of the dam lake

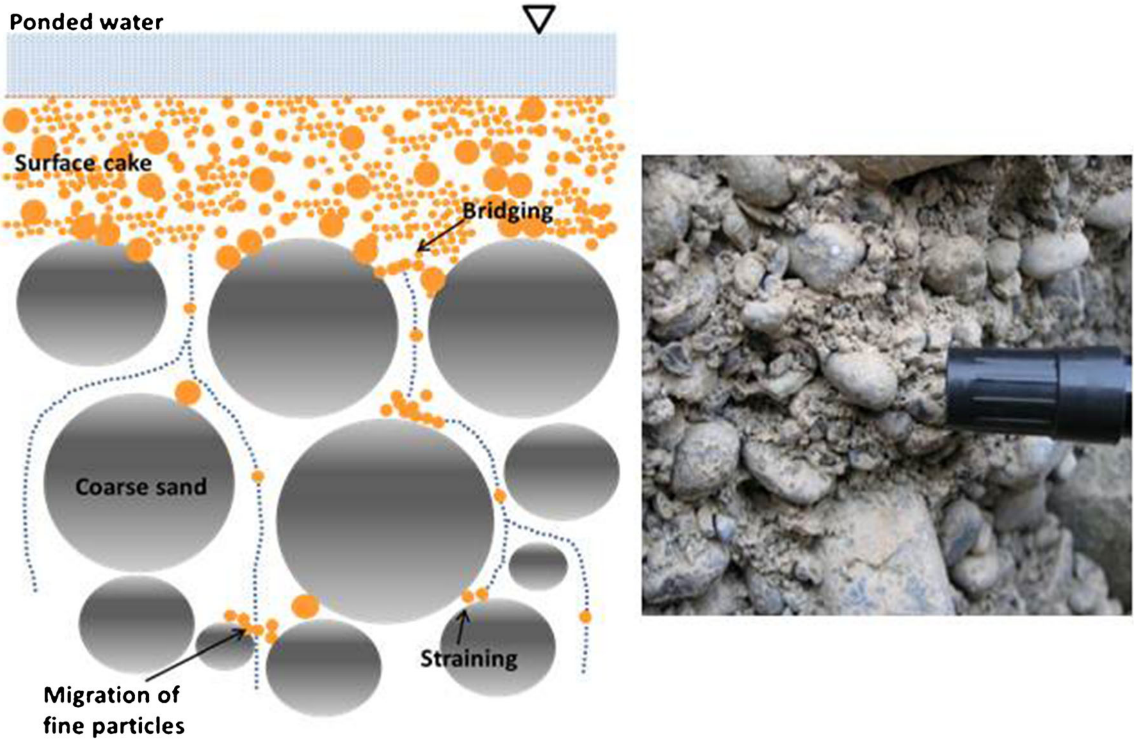


**Fig. 7** Physical clogging in between pebbles at a depth of 80 cm, attachment and detachment of fine soil particles within the coarse parent materials

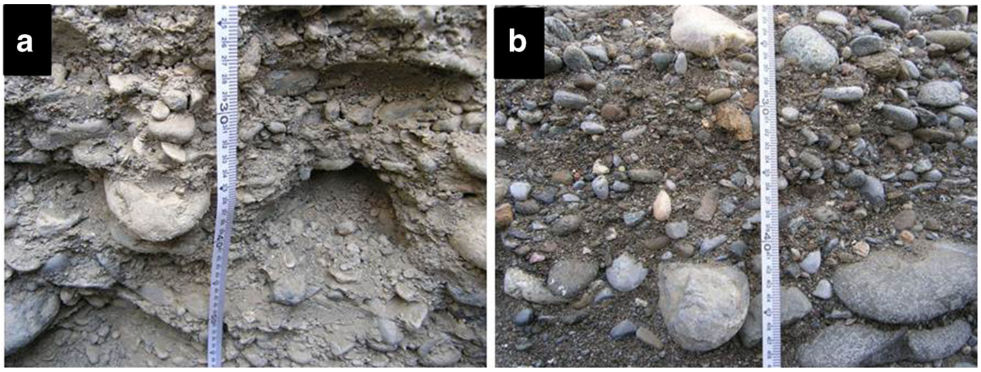
ranges from 2.16 to 2.5 m/day as in pedons AA and AC in Fig. 1, which is higher than that for heavily silted areas of pedon K with a value less than 0.02 m/day (Table 1). The conductivity is found to vary across the depth of the subsurface of the recharge basin. The $K_s$ drops from nearly 4 m/day at the surface to 0.37 m/day at a depth of 80 cm (Al-Ismaily et al. 2015). This could be attributed to the plastering of the soil fabric as a result of the translocation of the fine soil particles (Figs. 8a and 10a).

## Conclusion

Geotechnical structures, like recharge dams studied in this paper, exert pressure on the natural system by speeding up the physiochemical processes leading to quick soil evolution and development. The hydrological properties of the study area are changing due to scaling-caking problem caused by siltation. Soil textural variation with depth is evident in the Al-Khoud dam area. This siltation causes reduction in the dam storage capacity which is estimated to be more than 30 % (2275 $m^2$ per unit width of the dam wall) of the designed storage at construction time. Total volume of water that the dam can store in 2012 is assessed to be nearly 8 instead of 11.7 $Mm^3$ as originally designed, leading to frequent overspilling of the captured sediment-rich flash floods to the recharge basin.

Part of these finer particles migrates downward into the coarse gravelly soil materials causing physical clogging and, hence, reducing the subsurface conductivity by 10 orders of

**Fig. 8** **a** Plastering and dense structure in the subsurface of a parent soil inside the dam as compared to **b** loose sand and gravelly structure which is common in soils outside the reservoir area



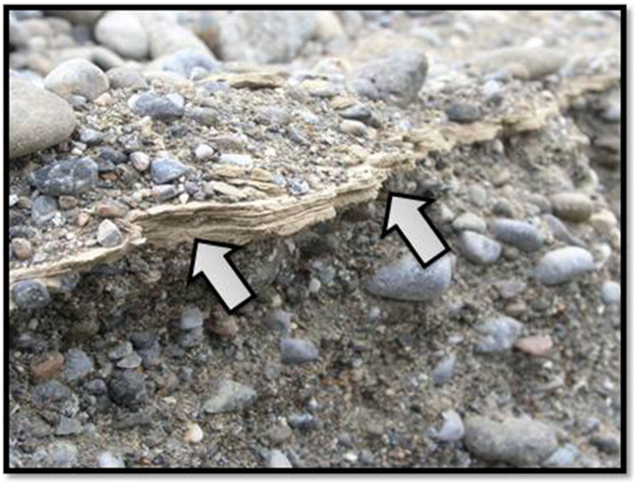


**Fig. 9** Formation of a thin surface caking on top of a coarse parent material in soils of the recharge zone

magnitude in some areas. In general, the infiltration downstream of the dam is relatively high (6 m/day)—compared to that inside the dam (0.15 m/day—in average for densely silted area) and 2.1 m/day for areas that are slightly silted in the upstream part of the dam—but less than that for the area that is not subjected to flooding except to sheet flow (7.3 m/day). With time, the conductivity of those areas may further decrease as more siltation and plastering of the soil fabric are expected to take place, regardless the current practice of the mechanical surface scraping of the silt layer.

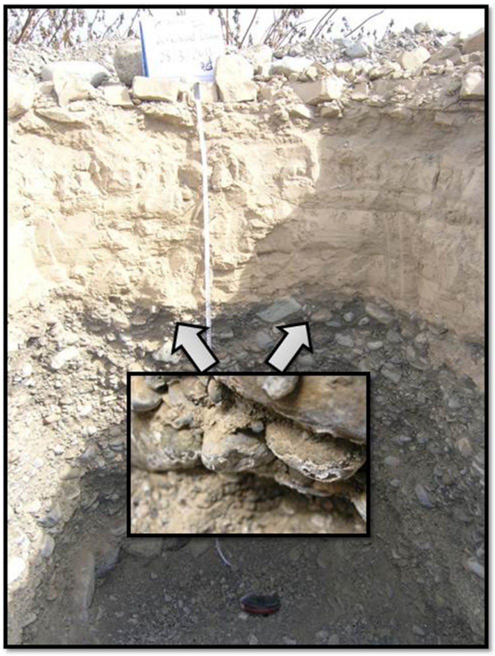


**Fig. 11** Thin discontinuous carbonate coatings on the undersides of pebbles and gravels at the interface between the top silt cake and the subsurface coarse material of pedon E

Due to the damming and during ponding periods, the infiltration water front continues to propagate into the soil carrying part of the dissolved calcic materials as an "intermittent process." Part of dissolved carbonates and gypsum is

**Fig. 10** SEM images taken from different subsamples. Image **a** representing subsample that is over-topped with surface caking and shows grains coated with fine particles and some pores that are clogged. Image **b** representing subsamples outside the dam (the original porous medium) and shows wide pore openings

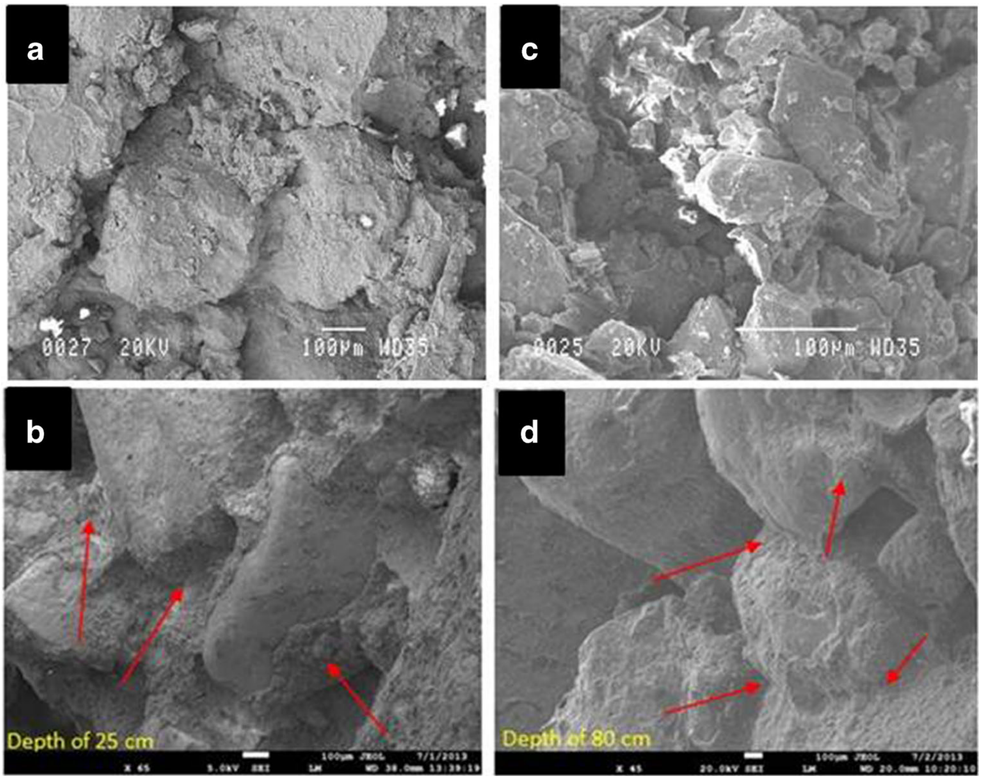


**Table 1** $K_s$ values of the selective pedons of the study area

| Pedon | Latitude | Longitude | $K_s$ (m/day) | $K_s$ (cm/h) |
|---|---|---|---|---|
| AA | 23.6219 | 58.1686 | 2.50 | 10.42 |
| AC | 23.6241 | 58.1574 | 2.16 | 9.00 |
| AG | 23.6217 | 58.1749 | 7.30 | 30.42 |
| I | 23.6294 | 58.1649 | 0.15 | 0.62 |
| K | 23.6273 | 58.1693 | 0.02 | 0.09 |
| R | 23.6493 | 58.1619 | 1.27 | 5.23 |
| S | 23.64852 | 58.17075 | 5.12 | 21.33 |
| W | 23.64912 | 58.16000 | 5.7 | 23.75 |
| $O_{surface}$ | 23.64725 | 58.15698 | 3.96 | 16.50 |
| $O_{80\ cm}$ | 23.64725 | 58.15698 | 0.37 | 1.54 |
| V | 23.64136 | 58.17596 | 9.08 | 37.83 |
| T | 23.64293 | 58.16865 | 8.1 | 33.75 |
| W | 23.64912 | 58.16000 | 5.7 | 23.75 |
| P | 23.64014 | 58.15859 | 6.9 | 28.75 |

transported vertically downward to reach high depths (in average 90 cm). This translocation results in coating of the sand grains, and may further create hard pans that will act as a low-permeable barrier, which impedes percolation of water to the aquifer and hence affects the hydropedogenic properties of the original soils.

**Acknowledgments** The authors would like to thank Sultan Qaboos University for the support. This work is part of DOPSAR project" Effects of siltation behind Al-Khoud dam on the soil properties and recharge efficiency" IG/AGR/SWAE/10/02.

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