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Status of sedimentation in King Talal Dam, case study from Jordan

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Abstract This paper focuses on characterizing the current status of physical and chemical characteristics of King Talal Dam (KTD) sediments. The quality of sediments was investigated based on several international sediment quality guidelines. The volume of sediment and sedimentation rate in (KTD) was also estimated. Five types of granulometric textural facies were observed for the sediments of KTD reservoir bed, with an average grain size distribution of gravel (1.38%), sand (32.38%), silt (32.35%) and clay (32.38%). The fraction of <63 micron showed that the total mean size was 8.0 micron. Other sediment parameters in KTD were 7.0% for total organic matter (TOM), 7.3 for pH, 35.9% for $CaCO_3$ and 100.5 meq/100 g for cation exchange capacity, with dominant mineralogical constituents of quartz, calcite, dolomite, clay minerals and minor feldspar. The total concentrations of F, Cl, NO_2, NO_3, PO_4 and SO_4 in sediment samples were lower inward for KTD. The vast majority of trace metals in sediments were generally within the standard limits recommended for soils. TOM and grain size of sediment are major factors governing the trace metal concentrations. The calculated geoaccumulation index (I_{geo}) and enrichment factor of metals in bottom sediments showed that the metals were in the following order: Cd > Pb > Zn > Co > Cr > Ni > Fe > Cu > Sr > Mn and Cd > Zn > Pb > Co > Cr > Ni > Cu > Sr > Mn, respectively. Based on the sonic survey of KTD reservoir, the annual sedimentation rate was about 0.4061 MCM/year, in which about 18.66% of the reservoir initial storage capacity was lost to sediments and a projected lifespan of about 198 years.

Keywords Textural facies · Metals · Sediment quality · King Talal Dam · Jordan

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Introduction

King Talal dam (KTD) (Fig. 1a) is an earth-fill dam that was constructed in the period from 1977 to 1978. The total storage capacity of the dam is 88.5 million cubic meters (MCM) with a dead storage of about 8 MCM (live storage capacity is 80.5 MCM). The reservoirs lake is about 7.6 km long with a maximum width of 450 m. KTD catchment is about 33.75 km². The dam lies within the Zarqa River basin and was designed for irrigation and electricity generation.
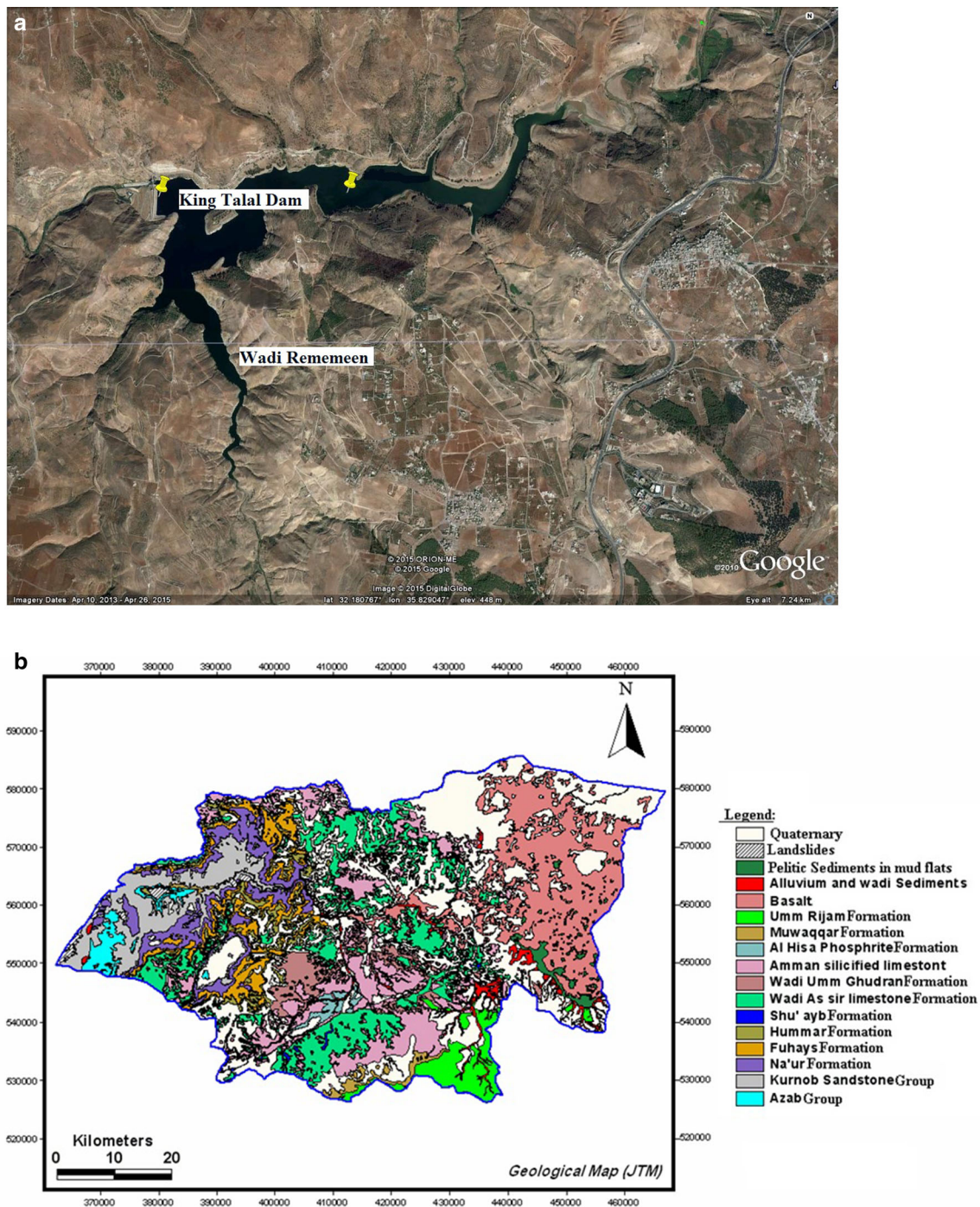
Significant industrial activities of Jordan are located near the Zarqa River, and their wastewaters are frequently discharged (either accidentally or intentionally) into the river with higher contents of heavy metals and toxic substances (Hashwa 1985; Ghrefat et al. 2012). Wadi Rmemeen drainage (Fig. 1a) containing wastewater from Baqa'a treatments plant and spring waters represents the second important source of water discharged into the dam (RSS 2005). The water quality of KTD has been adversely affected by discharge of effluent of Khirbet As-Samra and other industrial wastewater, containing relatively high concentrations of heavy metals, phosphorus and ammonia, into the dam through Zarqa River (Al-Jassabi and Khalil

Fig. 1 a Photograph of KTD reservoir modified (after JICA Expert/ Sabo and Landslide Technical Center Expert/Sabo 2013. Japan. Sediment countermeasures for dam's reservoir, Akihiko IKEDA).

b Geological map of Zarqa River basin (including KTD catchment) (after Al-Rawabdeh et al. 2013)

2006; RSS 2005). In addition, this has limited the use of its water (the dam's water is used for irrigation only). Sediment quality of the Zarqa River seemed to have been slightly improved alongside flow direction, but uncontrolled discharges of domestic and industrial effluents into the Zarqa River were recorded (IDRC 2006).

Zarqa basin (containing KTD catchment) is part of the Mediterranean climate, with an arid climate in the southeastern and eastern regions and rainy humid conditions in the west. Humidity and precipitation decrease rapidly from KTD toward the eastern deserts (USAID and WAJ 1989), with an average annual precipitation of 300 mm

(commonly occur as flash floods). Higher rates of sedimentation occur from September through April as a result of higher rainfall and runoff erosion efficiency (increased the rate of rock and soil weathering and leaching of soluble elements). The most significant loads of nutrients are transported to surface waters from agricultural catchments (Horák and Hejcman 2016). Reservoir sediment is an important geo-environmental concern because sediment may act as a source of nutrients and can decrease the dam storage capacity. The objectives of this work are: characterization of KTD sediments, assessment of sediment quality and estimating the dam's lifespan.

General setting

The sources of KTD bottom sediments are directly related to the outcropping formations in the catchment, ranging from Lower Cretaceous to recent age, where the Cretaceous sediments are most dominant. The geological map of the entire Zarqa basin is presented in Fig. 1b. According to Masri (1963), the main lithostratigraphic succession (in ascending order) is as follows:

Wadi Es-Sir Formation A7 (Turonian) crops out extensively in the northern, central and southern parts of the catchment. The massive crystalline limestone is karstic and weathered in the top 20 m of the formation, below which is a general increase in the marl chalky limestone and thin marl beds occur.

Amman Formation B2 (Santonian-Campanian) is a successive deposit of chalk, phosphate, silicified phosphate, limestone and chert, with a thickness of more than 47 m.

The Basalt Plateau (Oligocene–Pleistocene) is composed of basalt and crops out in the northeastern part of the basin. Thin layers of clay and gravel (of limestone and chert pebbles) occur between the successive Scoriaceous basalt and volcanic plugs basalt flows.

Younger Alluvium Formation (Wadi-fill and alluvium deposits) of Quaternary age consists of thin deposits overlying the basalt in the cemented outwash and the old river terraces. River and superficial gravels and silts are widespread (Fig. 2). These are underlain by Kurnub sandstone Formation of Lower Cretaceous that outcrops along Zarqa River valley with coal- and organic-rich Amber Beds (Harald et al. 2009).

The Zarqa basin is subdivided into two main catchments: Wadi Dhuleil sub-basin representing the arid conditions and flat land, and Zarqa River sub-basin which represent the most populated mountainous area. The Zarqa basin extends from the foothills of Jabel Al-Druz Mount at elevation of 1580 m above sea level in the southwestern Syria, to its estuary in the Jordan River at elevation of 370 m below sea level. The lower part of the Zarqa River forms part of the Jordan Rift Valley. Both branches meet at Sukhna region to form the Zarqa River. The total catchment area is about 3918 km^2 (RSS 2005), with 89% located in Jordan and 11% inside the Syrian territory.

The inclination of topographic reliefs of KTD catchment led to an increase in the rate of topsoil and rock erosion, and transport of chemicals, organic materials and nutrients directly into the reservoir. In addition, the relatively steep topography (where the eastern side is relatively milder than the western area) allows for serving remote communities by wastewater treatment plant. In the eastern area, Dhuleil pumping facility is required to lift the flow up to the inlet.

Soil erosion on the steeper slopes of the catchment is the main cause of colluvial processes, where sheet erosion is more pronounced in the western part. Overgrazing, deforestation and agricultural activities as well as construction activities have increased the sediment load. KTD receives an annual average sediment load of 0.625 MCM, containing plant debris, heavy metals and other toxic and chemical (Ghrefat et al. 2012). Chemical pollutants incorporated into the sediments may be released into the water threatening water quality of KTD.

Different types of soil erosion threaten the storage capacity of KTD. The upper slopes are affected by soil erosion and degradation, resulting in a shallow and stony soil. The soils in the catchment are widely varied depending on rainfall and relieves, where the soil becomes darker with increasing depth. Reddish to brownish clay and clay loams are dominant in the northwestern catchment, where precipitation is higher. The soil becomes more immature eastward with silty loam to loamy texture, yellowish brown to strong brown with very high carbonate content (Al Mahamid 2005). Most soils of Zarqa River catchment were found to be probably polluted or potentially polluted with Pb, Cd and Ni (El-Khattari 1986; Al-Ghazzawi 2010).

Two types of soil association units were found in the Zarqa River catchment. The first unit is the Nisab (NIS) which has an average depth of <80 cm and is composed of silty clay loam and clay loam. The second soil association unit [known as Abu Salih (ALI)] is characterized by deep (more than 80 cm) silty clay with highly calcareous and nonsaline in some parts and very shallow (less than 25 cm) gravely silty clay loam on limestone. The land use/cover types in the catchment of Zarqa basin are bare rocks, thin soils and urbanization (65%), and natural vegetation, forest, irrigated and rained agriculture (35%), (Al Mahamid 2005).

Methods

Bottom sediments of KTD reservoir were sampled at the ending of spring 2013, corresponding to the end of the period of nutrient input by runoff. Forty surface sediment samples (1–15 cm depth) were collected from KTD
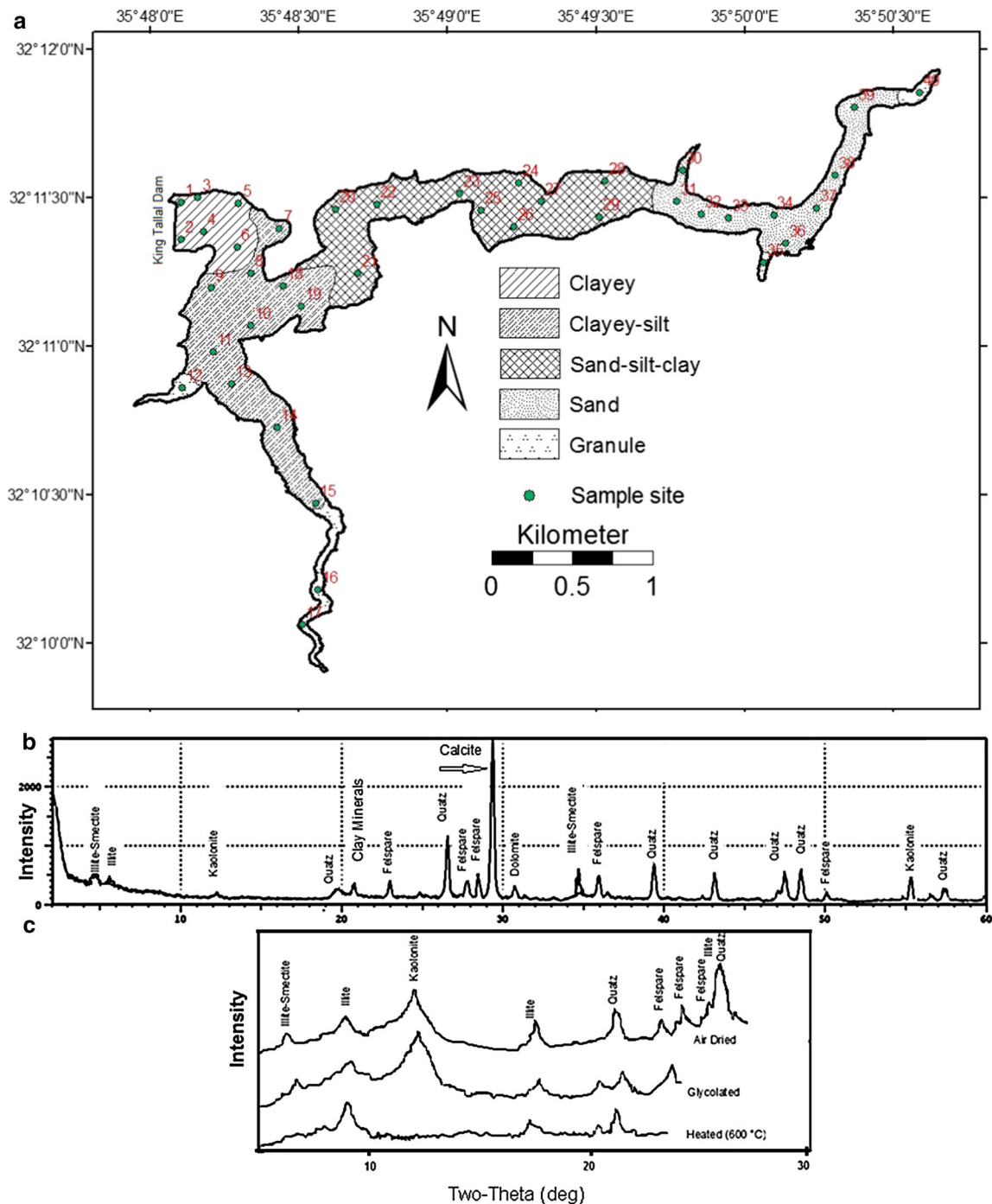
Fig. 2 a Sampling points and granulometric textural lithofacies map of KTD sediments. b, c X-ray powder diffractometer patterns of selected samples collected from bottom sediments of KTD

reservoir using a Van Veen grab sampler (sampling points are presented in Fig. 2a).

Samples were placed into polyethylene bags and transferred to the laboratory for further analyses. Sample preparation and handling were done according to Plumb (1981). Then stones and plant fragments were removed by passing the dried sample through a 2-mm sieve. Sediment samples were initially characterized for grain size

distribution, to produce a facies map (Fig. 2a). Following grain size analysis, samples were oven-dried at 55 °C and wet-sieved through a 63-µm sieve to separate the mud from other factions. The fine fraction (63 µm) was further analyzed with a Computerized Sedigraph Analyzer. The clay-size fraction was then separated from silt by the pipette method (Loring and Rantala 1992). Trace metals concentrations in sediments with particle size ≤2 µm were

investigated using the pipette analysis method (Williams et al. 2000). The solution of the digested samples was analyzed using the standard methods of Atomic Absorption Spectroscopy-model Philips SP 9PYE Unicam Spectrophotometer for iron (Fe),copper (Cu), zinc (Zn), manganese (Mn), cadmium (Cd), cobalt (CO), lead (Pb), krypton (Cr),nickel (Ni) and strontium (Sr). A comparison study between wet and microwave digestion of Cd, Co, Cr, Cu, Mn, Pb, Zn, Fe and Ni contents of the bottom sediments from the various locations of Turkey was performed by Tuzen et al. (2004) showing that the microwave-assisted digestions in closed system are easier and faster than the wet digestion. Also the results found by the microwave and the wet digestions were reliable and accurate. The relative standard deviations for all metal concentrations were found to be lower than 10%.

For quality control, triplicates of each sample were analyzed, and average values were calculated. Accuracy of the atomic absorption spectrometer analysis was checked using National Institute of Standards and Technology standard reference material SRM 1646 (estuarine sediment). Correlation coefficients between sediment variables were calculated with the SPSS software package. Six oriented clay samples were prepared to identify clay minerals in the mud fraction (Grim 1968) using XRD and Scanning Electron Microscope (SEM) methods, (Figs. 2b, c).

Samples were examined untreated, ethylene glycolated and heated to 600 °C (Fig. 4b). X-ray diffraction was conducted under the following conditions: $2\theta:0°-30°$; X-ray radiation: Cu kα; generator current: 30 mA; generator voltage: 30 kV; and scanning speed: 0.05 cm/min. Bulk mineral fractions (<63 μm) were also X-rayed for four samples by scanning at 1°/min in the range of 2θ from 5° to 60° (Fig. 2b). Total organic matter (TOM) in each sample was measured by the titration method (Hesse 1972). The calciometry method (Loring and Rantala 1992) was used to determine the content of carbonate $(CO_3)^{-2}$ in the sediments. In this method, the amount of CO_2 released from the reaction is dependent on the amount of $CaCO_3$ in the sample.

Results and discussion

Sedimentation processes

Sedimentation rate is an issue of concern in the KTD because it is relatively high with subsequent decrease in the reservoir storage capacity. It has been reported that the KTD is suffering from irregular annual sediment deposition (Al-Sheriadeh and Al-Hamdan 1999; Malkawi et al. 2002) and the sediments entering the reservoir contain nutrients and heavy metals (Abu Hilal and Abu Alhaija 2010).

In spring of 2015, a bathymetric survey study was carried out under a cooperative agreement with JVA (using their sonic depth recording equipment) to estimate the sediment volume in KTD and the annual average sedimentation rate and calculate the lifespan of KTD. Thirteen echo sounding survey lines were conducted to cover the majority of the KTD reservoir, distribution and locations of survey lines are presented in Fig. 3.

The survey results are schematically illustrated in Fig. 4. The cross-sectional profiles showed the sediment, water and base levels in KTD. Base map of the dam's bottom showing the pre-dam topography is not available, and the calculations were based on a constant base level of about 124 m (Fig. 4).

The results showed that the total volume of sediments in KTD reservoir is 15.024844 MCM (accumulated from 1978 to 2015). This indicates that the estimated long-term sedimentation rate in KTD is about 0.4061 MCM/year during 37 years of operation.

Based on the initial storage capacity of KTD of 80.5 MCM, the rate of silting up at KTD is 0.504% per year, indicating that approximately 18.66% of the reservoir's initial storage capacity has been lost to sediments (after 37 years of operation). According to these calculations, it is expected that KTD will be completely silted up in 2213. Therefore, if the physical, chemical and biological conditions in KTD catchment remain relatively unchanged, the life span expectancy of the reservoir is about 198 years.

Summary of annual sediment volume, cumulative sediment volume and the annual water entering KTD is presented in Fig. 5. The flood volume showed a cyclic pattern of ups and downs with a general increase in the quantities of water discharged into KTD. However, the annual sediment quantities transported to KTD showed generally slight increase with few exceptions. The sediment load peaked in 1981 and in 1992. It appears that sediment influx and flood volume are not strongly related suggesting that the sediment loads are probably dependent on other factors. In addition to the amount of water discharged into KTD reservoir, the nature of rainfall precipitation is likely to play a role, where flash floods are likely to mobilize more sediment. Furthermore, an increase in sediment volume is associated with an increase in arable land and agricultural activities in KTD upstream catchment (particularly plowing).

Pastoral activities and overgrazing also increased the rate of soils erosion and sediment influx to KTD reservoir. From 1997 to 2015, there have been relatively similar quantities of sediments entering KTD (Fig. 5). Prior to the 2015 survey, the last estimate of sediment quantities was carried out in 2009 with an annual average sedimentation rate of about 0.437 MCM. From 2009 to 2015, the
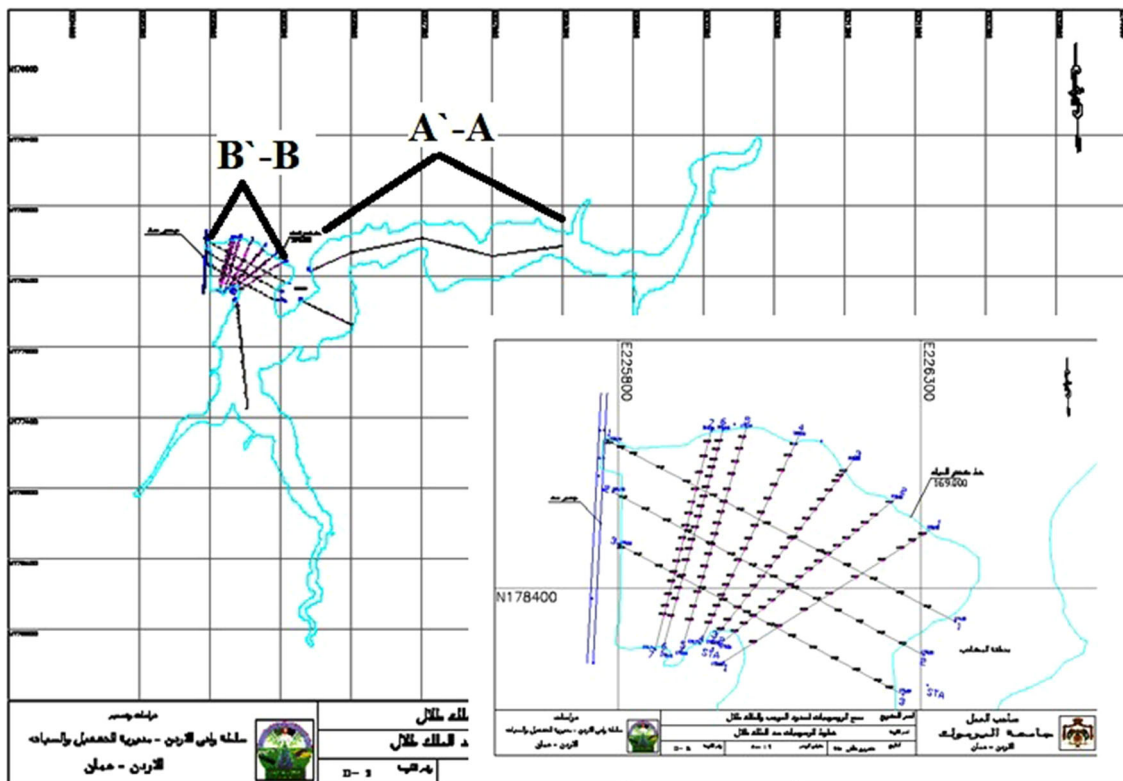
Fig. 3 Echo sounding surveys conducted to estimate the sediment volume in KTD

estimated annual sedimentation rate is about 0.248 MCM. These results indicate that the annual sedimentation rate in KTD has substantially decreased. This is probably attributed to protective measure and enhanced landuse planning in the catchment, though the occurrence of flash flood has increased (expected to increase the sedimentation rate).

The prevailing Mediterranean climate, with high rainfall intensity particularly during the winter, is likely to increase the intensity of weathering and erosion by rainfall and runoff, where the majority of very fine fraction is settled down during the dry seasons (due to the abrupt lowering in the hydrodynamic activity). Sediment discharge is composed of wash load (silt, clay and dust) which remains suspended until reaching the reservoir. Suspended particles are continuously supported by turbulence of the water flow. Bed load is transported as saltation, sliding and rolling during high agitated flow regime.

Data obtained from grain size analysis were used to draw the cumulative frequency curves for tow representative samples on a logarithmic probability graph paper (Fig. 6). Accordingly, any deviation from a straight line is considered anomalous, whereas the slope of curve is dependent on the sorting of the curve as function of the sediments and the position of the curve is the function of the grain diameter (Folk 1974). Natural grain population

frequencies follow several straight-line segments, which are related to the mode of deposition, and every segment might be attributed to a specific type of deposition or transportation process.

As mentioned earlier, KTD is located in Zarqa basin, which is characterized by heterogeneous geology, intense agricultural activities and relatively polluted soils. The physical, chemical and mineralogical characteristics of bottom sediments are a result of long-term erosion and weathering of parent material. These processes results in physical disintegration and chemical decomposition of minerals and the release of metals from the parent material to KTD. A close relationship between the metal content of the parent material and bottom sediments has been observed in a number of studies (Fonseca et al. 2003, 2011; El-Radaideh et al. 2014; Al-Taani et al. 2015; El-Radaideh 2016).

The wide diversity in geology and physiography of KTD catchment gives a wide range of sediment sources (and soil). The main byproduct of selective weathering, selective erosional processes of soil profiles and unconsolidated rock profiles are the clay mineral particles. These clay particles with high adsorbability to micro- and macro-nutrients are the most sensitive to weathering, due to its low density and size (Fonseca et al. 2003). Different types of alterations: chemical, biological and mineralogical

Fig. 4 a Cross-sectional profile (B′-B, A′-A) in KTD dam reservoir presenting the 2015 surveying results conducted by JVA (combined 2 survey lines). **b** Illustrative transverse section showing the base, sediment and water levels in KTD following the 2015 survey
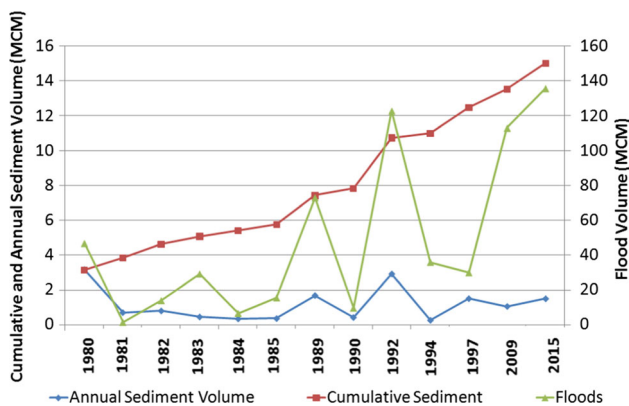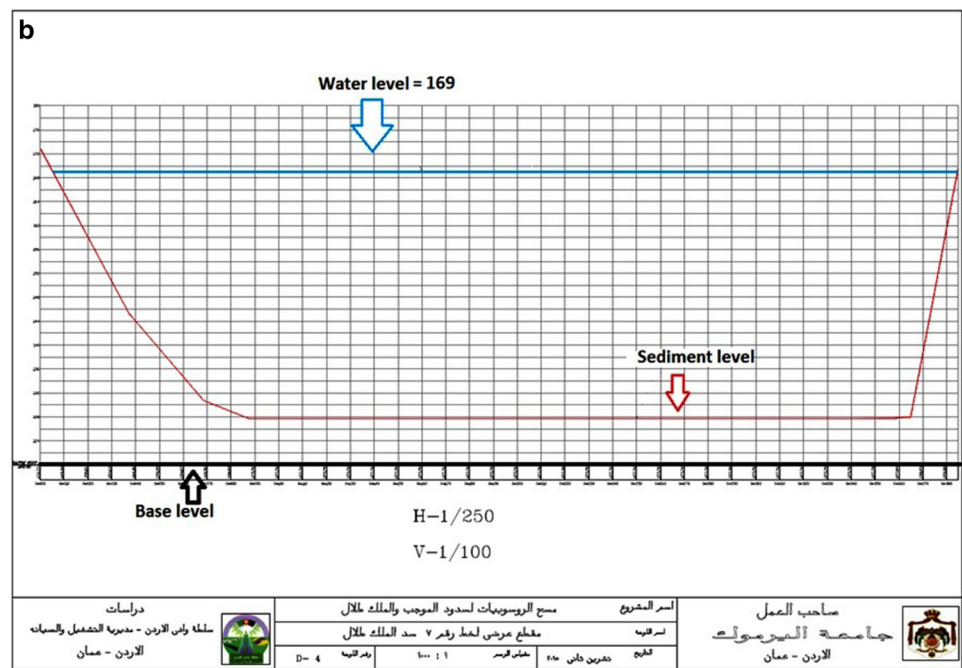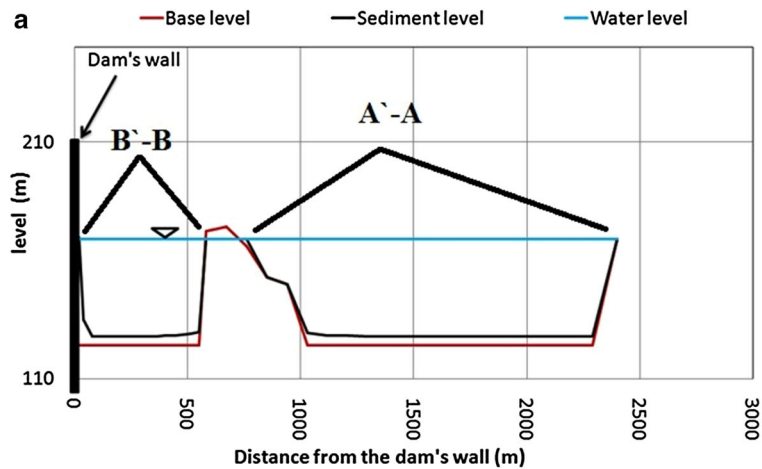

Fig. 5 Summary of sediment and flood volumes in KTD from 1980 to 2015

transformational processes to the outwash/suspension fractions occur during weathering, transportation and deposition in reservoir. These transformational processes are more pronounced in the northwest sector of the catchment owing to the relative higher rainfall intensity.

Fonseca et al. (2003) stated that "the most important chemical elements for fertility of bottom reservoir sediments under total forms are far exceed the corresponding medium values for soil in general and for parent soils." This suggests that the bulk sediments of KTD can potentially be of agricultural use (also based on our results). The abundance of total forms of sediment nutrients is enhanced by decreasing sediment size fraction (Fonseca et al. 2011; El-Radaideh 2016).

Fig. 6 a Cumulative percentage of virus's diameter for two bottom samples collected from KTD sediments. b Granulometric textural distribution of KTD sediments. c Representative sample of sedigraph analysis of KTD sediments
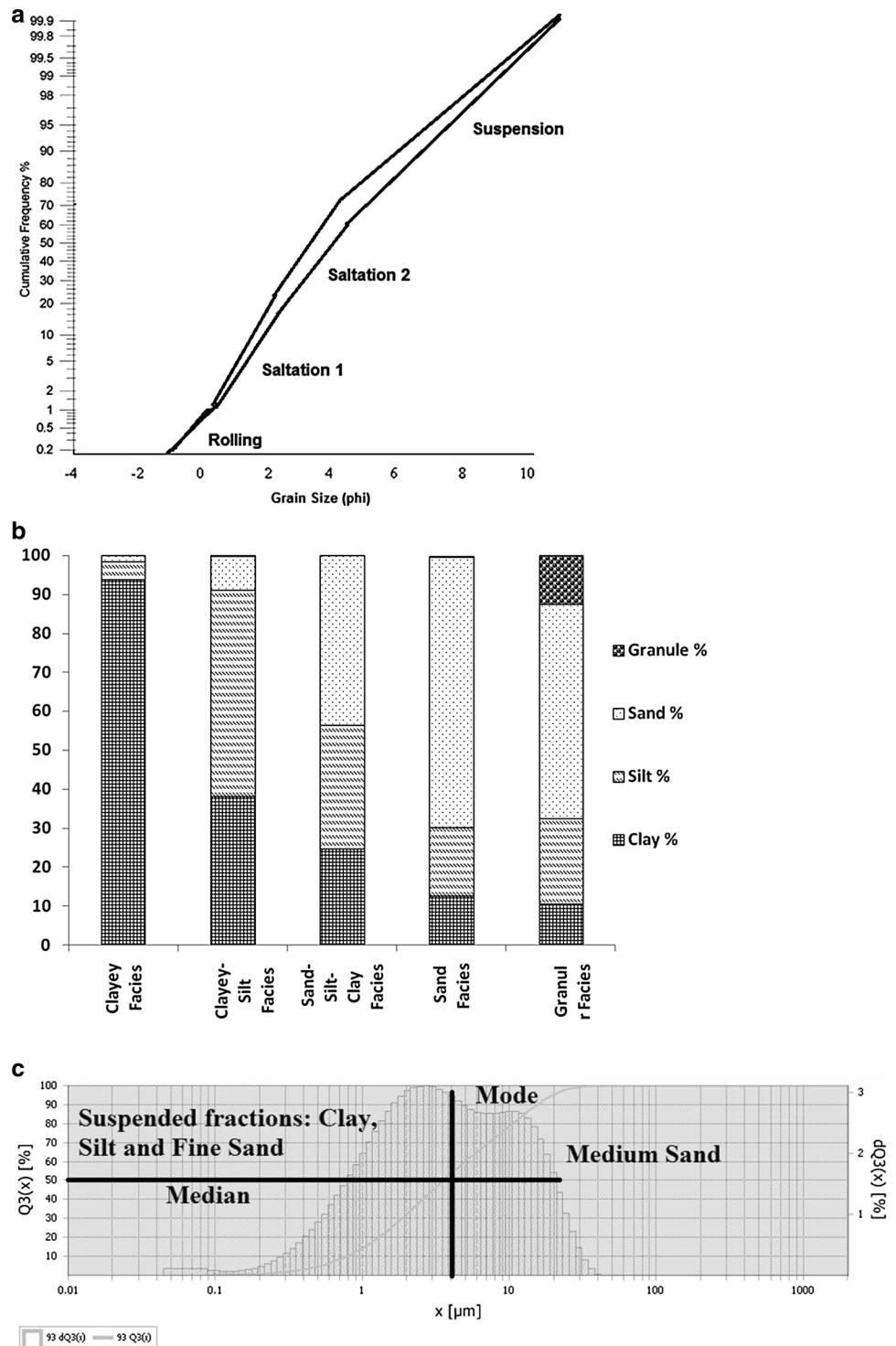
The granulometric distribution of the surficial KTD reservoir sediments signifies the importance of catchment lithology and physiography. Grain size distribution was comparable with the major distribution of fine-grained material detected in other similar systems (Fonseca et al. 2003; El-Radaideh et al. 2014; El-Radaideh 2016). The grain size analysis of the reservoir bottom sediments indicated that KTD reservoir bed is mainly covered by granule (1.38%), sand (32.38%), silt (32.35%) and clay (32.38%) (Figs. 2a, 6b, and Appendix 1 of ESM). The overall sediments fall in the following textural facies: clayey, clayey-silt, sand-silt–clay, sand and granular.

Sediment transport is a direct function of water movement. During transport mechanisms from surrounding

catchment of KTD area, sediment particles become separated into suspended fractions (silt, clay and fine sand), bed load and the saltation load. The slight increase in the finer fraction (<4 μm) as illustrated in the sedigraph plots (Fig. 6c) could be the result of seasonal runoff due to the variable seasonal discharge water or it can also be related to the starting of agricultural season in KTD catchment (with intense plowing). In addition to cultivation, overgrazing has increased the rate of topsoil erosion. The expansions of agricultural activities, particularly in El-Dhliel area, are more concentrated in northwestern catchment. Overall average size of KTD sediments is 9.0 μm.

Quality evaluation of KTD sediments

Bottom sediment characteristics

Total concentrations of trace metals and physicochemical parameters are summarized in Appendix 1 of ESM. The granulometric textural facies presented in Figs. 2a and 6b indicated that common facies are the clayey, clayey-silt, sand–silt–clay, sand and granular facies.

The content of clay-sized particle in surficial sediments of KTD reservoir (Fig. 6b) was essentially important with respect to fertility. They are the most chemically reactive components that enhance the accumulation of the extraclasts organic matter. The average TOM content is 7.0% with minimum and maximum values of about 3.4 and 12.5%, respectively. These values are within the medium range for soil (2.5–7.5%, Donahue et al. 1983). In most reservoir sediments, these values are higher than the parent soils (Fonseca et al. 2003). The high TOM levels in KTD sediments suggest high tendency for the sediments to collect organic compounds. Moreover, the relative high TOM values observed in KTD sediments could be attributed to high energy regime during high agitated storm events, leading to accelerated rate of allochthonous input of organic materials into the reservoir.

The average pH value of the reservoir sediments was 7.3, with minimum and maximum values of 6.8 and 8.0, respectively (Appendix 1 of ESM), which is indicative of the buffering effect of calcareous rocks of the watershed area. Based on Donahue et al. (1983), these values are suitable for availability of most micronutrients (trace metals) in soils (Appendix 1 of ESM).

The carbonate content ($CaCO_3$) in KTD sediments ranged between 28.9 and 43.4%, with an average value of 35.9% (Appendix 1 of ESM). The high content of $CaCO_3$ is mainly derived from weathering and erosion of exposed carbonaceous deposits in the catchment. Positive correlations were observed between $CaCO_3$ content and Cu, Zn, Cr, Pb, Cd, Mn and Sr, with $r = 0.14, 0.42, 0.26, 0.31, 0.41, 0.32, 0.11$, respectively. The positive correlation coefficients suggest that

these trace elements are, at least, partially associated with each other. Positively weak correlations were observed between pH and Fe, Cr and Cu with $r = 0.12, 0.20$, and 0.12, respectively (Appendix 2 of ESM).

The cation-exchange capacity (CEC) in the reservoir sediment ranges between 43.0 and 149 meq/100 g, with an average value of 100.5 meq/100 g (Appendix 1 of ESM). According to Cottenie (1980), these values are within the normal range for soils of 100–175 meq/100 g. High CEC observed in the fine granulometric textural facies is related to variable and high content of clay minerals. High levels of CEC would enhance the availability of metallic micronutrients (Spisto 1989; El-Radaideh et al. 2014; El-Radaideh 2016). High positive correlations were observed between CEC and clay content ($r = 0.73$) and between CEC and TOM ($r = 0.66$) (Appendix 2 of ESM). These correlation coefficients suggest that the different physicochemical parameters of KTD seem to compete for trace elements and that the trace elements are associated with one another (although they appeared to have different natural and anthropogenic sources, as explained later). The high values of total micronutrients (trace elements), CEC and the high clays content contribute significantly to sediment fertility (Spisto 1989; Fonseca et al. 1993; Fonseca et al. 1998; Junakova and Balintova 2012).

Mineralogical composition

KTD sediment samples were assessed by XRD and SEM (Figs. 2, 7). Similar mineralogical composition was generally observed in the majority of the textural facies, where quartz, calcite, dolomite and clay minerals are dominated with minor feldspar.

Clay minerals were largely composed of kaolinite, illite and rarely montmorillonite-smectite. Montmorillonite clay minerals appear as irregular aggregates. Differences in substitution, camouflage and capturing processes probably affect its forms and shapes. Illite usually occurs in KTD sediments as poorly defined flakes and irregular aggregates. Illite particles of coarser sizes have also been detected. Irregular kaolinite particles were observed within the detrital quartz matrix (Fig. 7). The mineralogical constituents reflect the major geology of catchment area, where carbonate, sandstone and basaltic rock flow occur in KTD watershed.

Trace metal content

The average concentrations of Fe, Cu, Mn, Co, Ni, Cr and Sr were 44445.5, 30.26, 275, 25.6, 42.6, 79.37 and 117.97 mg/kg, respectively. These values are lower than their average concentrations in continental crust (Fortescue 1992). However, the mean concentrations of Zn, Cd and Pb
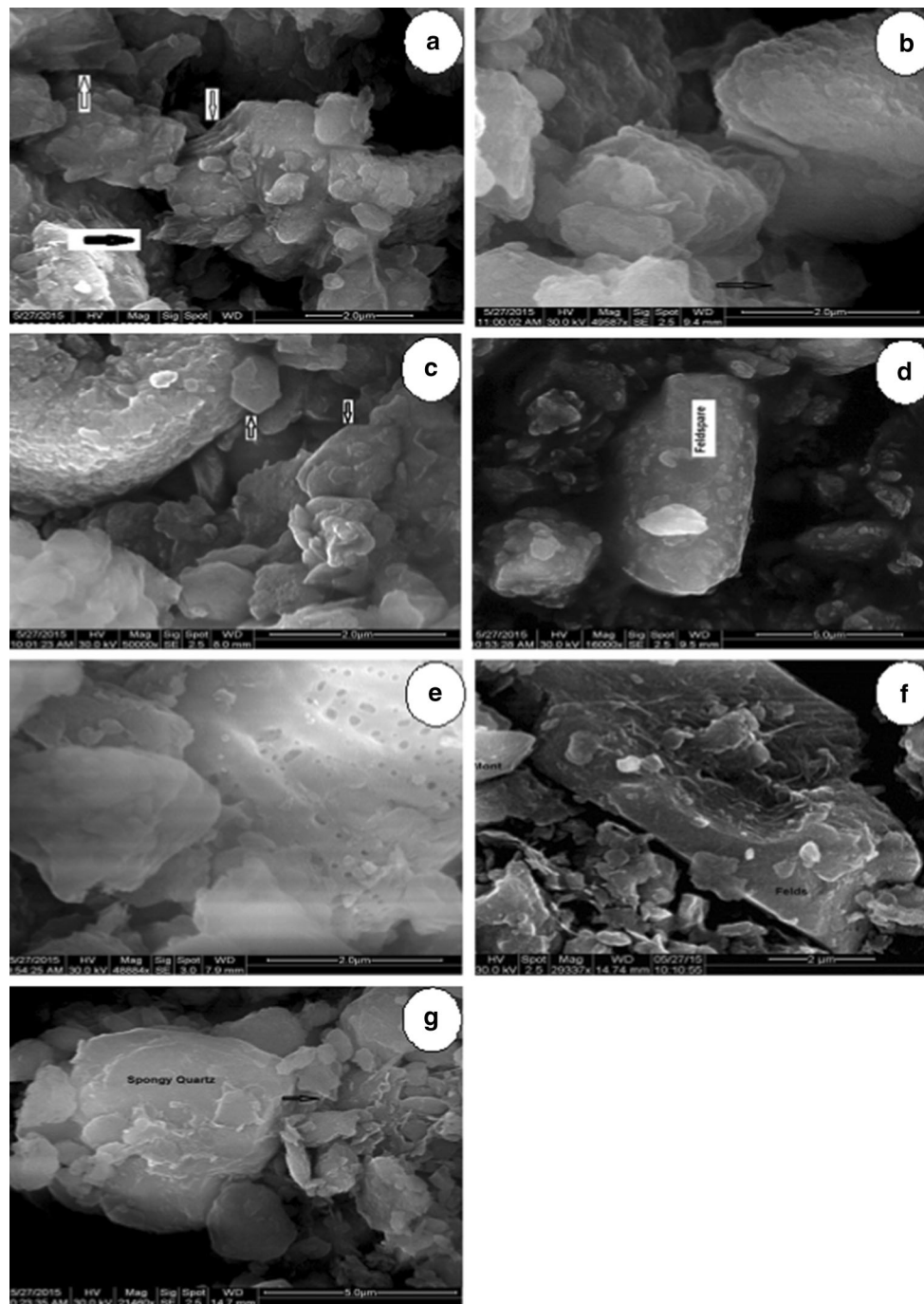
Fig. 7 SEM images showing: **a** general aspect of the clayey silt facies; the *white arrow* indicates the presence of sheets of open micas-smectite, *black arrow* indicates alteration of illite to smectite showing honeycomb smectite formation in KTD sediments. **b** Kaolinite with typical booklet structure, illite (*arrow*) chemically converted from kaolinite (the flaky fragments just to *left of center*); the ribbons of illite to the *right bottom of center*. **c** Sand silt clay facies include euhedral (*arrows*) quartz grains indicate short distance of transportation, eroded from nearby Kurnub sandstone formation within a detrital quartz aggregate lithology in KTD sediments. **d** Sand silt facies include feldspar grains within detrital sediments. **e** Radial pattern of regular ovoidal-elliptical pours ornamentation of spine shell of microfossils. **f** Aggregates of irregular hexagonal flakes and laths of montmorillonite above partially altered feldspar grain. **g** Platy and lath-shape particles (*black arrow*) with broken edges and patches of Kaolinite and large spongy quartz particle

of about 373.51, 17.85 and 76.46 mg/kg, respectively, exceed their average levels in shale (Turekian and Wede-pohl 1961) and crustal values (Fortescue 1992) (Table 1).

Fe, Cu, Mn, Co, Pb and Sr levels are comparable to the medium values of normal soil. The total concentrations of the Fe, Ni and Zn are near the medium range values of

Table 1 Mean concentrations, average crustal abundance, average shale in mg/kg (dry wt.), and mean geoaccumulation index (I_{geo}) and enrichment factor (EF), the world mean metal soil concentration, KTD mean metal in soil of the catchment area (Al-Ghazzawi 2010), average trace metals in KTD sediments and the maximum metal concentration in sediment from the River Yeşilırmak in Tokat, Turkey (Mendil et al. 2010)

Metal	Mean concentration in KTD sediments	Geochemical Background Continental Crust (Fortescue 1992)	Geochemical Background-Shale Standard (Turekian and Wedepohl 1961)	I_{geo} (Mean shale) (Turekian and Wedepohl 1961)	I_{geo} (Mean Crustal abundance) (Fortescue 1992)	EF (Mean shale) (Turekian and Wedepohl 1961)	EF (Mean Crustal abundance) (Fortescue 1992)	The world mean metal soil concentration	Mean in soil of KTD catchment (Al-Ghazzawi 2010)	The maximum metal concentration in sediment from the River Yeşilırmak in Tokat, Turkey (Mendil et al. 2010)
Fe	44,445.5	63,000	46,700	−0.2	−0.306	–	–	38,000[a]–40,000[b]	–	35,660
Cu	30.26	55	45	−0.35	−0.43	0.7	0.78	14–109	199.3	38.7
Zn	373.51	70	95	0.42	0.543	4.13	7.5	64	671.67	45.5
Mn	275	900	850	−0.657	−0.69	0.34	1.4	437[a]	–	463
Cd	17.85	0.2	0.3	1.6	1.77	62.78	126	0.41	148.74	0.55
Co	25.6	30	19	0.06	−0.1347	1.8	1.57	54	–	–
Pb	76.46	12.5	20	0.41	0.6	4	8.7	27 (3–90)	530.33	17.3
Ni	42.6	75	68	−0.24	−0.28	0.9	1.1	29	2291	79.2
Cr	79.37	100	90	−0.23	−0.276	0.923	4.9	11–22	98.91	–
Sr	117.97	375	300	−0.582	−0.677	0.41	0.44	240[b]	–	–

[a] (Kabata-Pendias and Mukherjee 2007)

[b] (Shacklette and Boerngen 1984)

normal soil, whereas Cd and Cr levels are in excess of the average concentrations in soils (Table 1). Fe, Ni and Zn metals are soluble and non-toxic to soils; the geogenic sources of these metals are chemical weathering and erosion processes at the upper catchment of the dam, where the basic volcanic (basalt) rocks occur (Olivine and Forsterite). Of these metals, only Cd and Cr may pose pollution problems. If these sediments are used as natural fertilizers (additives), and when exposed to air, these elements will be more oxidized, resulting in a substantial decrease in their availability to plants (Sparks 1995; Fonseca et al. 2003; Girmay et al. 2009). The highest concentrations of total trace elements were found in areas where fine particles (clayey, clayey silt, sandy-silt-clayey facies) are more dominant (Fig. 8), whereas the lowest concentrations were observed in area with high percentage of coarser particles (sand and granular facies). Many authors reported that trace metal concentration increased with increasing clay content and decreased with increasing sandy and pebbly content (Jones and Bowser 1978; El-Radaideh et al. 2014; El-Radaideh 2016). With little exceptions, most of the trace elements in KTD sediment are associated with the very fine-grained particle (Fig. 8) and with sampling sites of high TOM (Appendix 1 of ESM). Positive correlations between trace metal and clay and TOM contents were found (Appendix 2 of ESM).

We have currently no Jordanian guidelines for sediment quality in terms of acceptable concentrations of trace metals. Therefore, we have used a variety of sediment quality standards for evaluating sediment quality (Table 2).

For comparative study, the concentrations of trace metals in sediment samples from the Yesilirmak River in Tokat, Turkey are listed in Table 1 (Mendil et al. 2010). This study showing that a significant variation existed in metal content in different sediment sites and fish types reflecting that some of the fish species is accumulated trace metals at high ratio.

Cd concentrations in the KTD ranged between 2.0 and 27.0 mg/kg, with an average content of 17.85 mg/kg. These values are in excess of the NOAA, TEL, PEL, PEC, SLG, CSC and USEPA limits (Table 2). The average abundance of Cd in the earth's crust is 0.2 mg/kg, and in worldwide soils it is 0.41 mg/kg (Table 1). Cd in KTD sediment is likely associated with agricultural discharge containing phosphate fertilizers through diffusion processes. Limited pesticides and pigments of plastics industries in the catchment which are mainly composed of Cd sulfide, residuals of electrical, steel and Ni–Cd battery components are also considered significant sources (Mielke et al. 1991; Lindström, 2001). Increasing Cd concentration might be related to atmospheric emission (combustion of fossil fuel) and deposition of organic and fine-grained sediments.

Closer to proximal parts of the KTD catchment, agricultural activities with intensive use of fertilizers containing Cd are common (an average Cd content of up to 7 mg/kg). Again, the use of commercial P-fertilizers in agricultural soils in KTD catchment is a major source of Cd. This suggests Cd can be leached into KTD from top draining and subsoil runoff.

Positive correlations were observed between Cd and PO_4 ($r = 0.31$), $CaCO_3$ ($r = 0.41$), CEC ($r = 0.24$) and NO_3 ($r = 0.39$). Cd content was also correlated with other trace elements: Mn, Fe, Cr, Pb, Zn and Sr (Appendix 2 of ESM). These positive relationships suggest that these constituents are either adsorbed to or coated to very fine factions or are co-precipitated by oxides.

Fe concentrations in KTD varied from 33,446 to 59,879 mg/kg (averaging 44,445.5 mg/kg). No TEL, PEL or PEC guidelines exist for Fe. However, these values exceed the benchmark of 20,000 mg/kg for freshwater sediment at contaminated sites (Table 1). Primary sources of Fe are probably chemical weathering of basaltic rocks (which covered parts of KTD catchment).

Zn concentrations in KTD ranged between 33.0 and 2151.6 mg/kg, with an average of 373.5 mg/kg. Similarly, no TEL, PEL or PEC guidelines exist for regulating Zn levels. However, the average Zn is below the CSC but exceed the worldwide soil limits (Table 1). The average abundance of Zn in earth's crust is 76 mg/kg and in soils is 25-68 mg/kg. The permissible limit of Zn in sediment is 121 mg/kg based on USEPA (2002) standards. Possible sources of Zn are probably related to untreated wastewater. Mendil et al. (2010) published Zn values in sediment samples from Turkey as a maximum value of 45.5 mg/kg (Table 1).

Cu concentrations in KTD sediment fluctuated from 1.0 to 73.7 mg/kg, with a mean value of 30.26 mg/kg. These concentrations are in excess of the NOAA with negative effects might be observed on aquatic organisms. It appears that some textural facies contained higher Cu content which is likely linked to the use of Cu sulfate in the nearby wastewater treatment plants. The average total level of Cu is generally less than TEL, PEL, PEC, SLG, CSC and USEPA (2002) concentrations (Table 2). Cu concentrations showed positively moderate correlations with clay content, TOM, Cr and Sr, whereas weakly positive correlations with other parameters were identified. The average abundance of Cu in crust is 34 mg/kg, and in soils it ranges between 14 and 109 mg/kg. Mendil et al. (2010) study shows that maximum metal concentrations for copper (38.7 mg/kg) from Turkey exceeded (MacDonald)'s reported TEL value for copper (Table 1). Cu concentration being higher than the levels found in this study (Table 1).

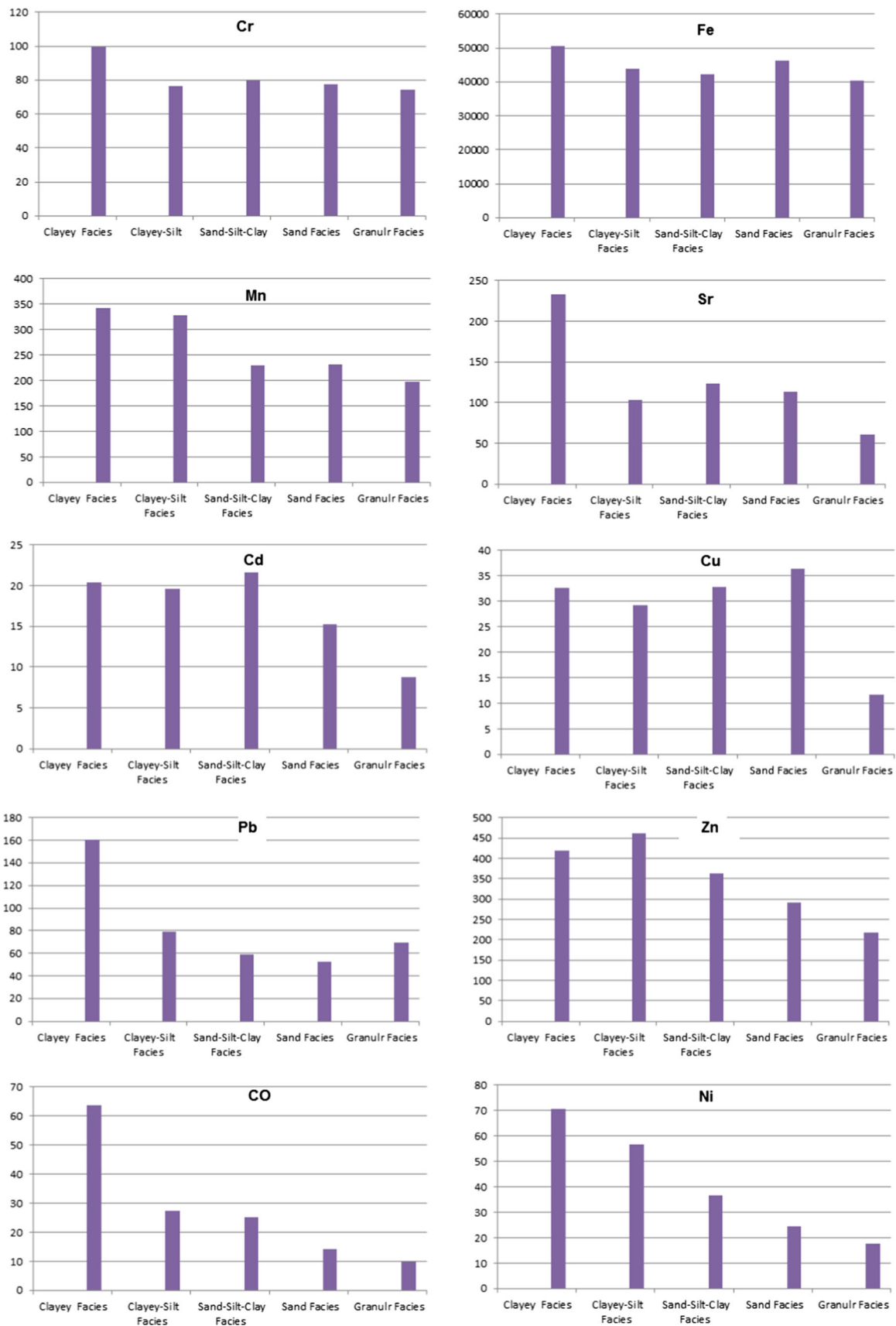High level of Cu might come from urban and industrial wastes.

Fig. 8 Mean trace metal concentrations (mg/kg) in the different lithofacies of KTD sediments

Table 2 Sediment quality guidelines of KTD sediments

Metal	Average concentration in KTD sediments mg/kg	NOAA	TEL	PEL	PEC	USEPA	SLG (severe concentration)	CSC
Fe	44,445.5	9900–18,000	NA	NA	NA	NA	–	–
Cu	30.26	10.0–25.0	35.7	197	149	31.6	110	60–125
Zn	373.51	–	–	–	–	–	–	70–400
Mn	275	400	NA	NA	NA	460	1110	1500–3000
Cd	17.85	0.10–0.30	0.596	3.53	4.98	0.99	10	3–8
Co	25.6	10	NA	NA	NA	50	–	25–50
Pb	76.46	4.0–17.0	35	91.3	128	20,000	250	100–400
Ni	42.6	–	–	–	–	–	75	100
Cr	79.37	0.70–13.0	37.3	90	111	43.4	110	75–100
Sr	117.97	–	–	–	–	–	–	–

(NA): not applicable

(NOAA): Typical background levels in US freshwater sediments

(TEL): Threshold effect level (concentration at which effects on aquatic organisms might be observed)

(PEL): Probable effect level (concentration at which effects on aquatic organisms will likely be observed)

(PEC): Probable Effect Concentrations from various agencies (McDonald et al. 2000)

(USEPA): Freshwater sediment benchmark USEPA freshwater sediment screening benchmark for use at remediation sites

(SLG): Screening level guideline of Ontario Ministry of environment (ANZECC and ARMCAZ 2000)

(CSC): Critical soil concentration ranges (Maiti 2003)

Mn concentrations in KTD sediment varied widely from 8.7 mg/kg to 503.3 mg/kg (with average of 275 mg/kg). These levels of Mn are lower than that in all sediment quality guidelines. Also, Mn concentration is lower than the normal range of soil (Table 1). Mn content in KTD sediment is below the safe limit of SLG and lower than the CSC range. A positive correlation with Ni and Zn was noted. Mn in earth's crust is 1060 mg/kg and in soils ranges between 61 and 1060 mg/kg.

Co concentrations in KTD sediment ranged between 7.0 and 77.0 mg/kg (averaging 25.6 mg/kg), which are higher than NOAA and less than all other sediment quality guidelines (Table 2). The critical and acceptable ranges of Co in soil are 25–50 and 4–20 mg/kg, respectively (Maiti 2003). Co is positively correlated with clay content $(r = 0.92)$, TOM $(r = 0.63)$, CEC $(r = 0.64)$, K $(r = 0.61)$ and Pb $r = 0.62$ (Appendix 2 of ESM). Possible source of Co is probably the decay of cyanobacteria and humic materials from nearby farms or industrial effluent discharged into KTD through Zarqa River.

Pb concentrations in KTD sediment varied widely from 12.0 to 178 mg/kg, with a mean content of 76.5 mg/kg. These levels of Pb are above the NOAA and TEL, but lower than PEL, PEC, SLG, CSC and USEPA benchmark concentrations (Table 2). The background level of Pb in natural soils ranges between 2.6 and 25 mg/kg (Maiti, 2003). Increasing Pb concentration might be related to atmospheric emission (combustion of fossil fuel) and

deposition of organic and fine-grained sediments (Massolo et al. 2012).

Cr content in KTD sediment ranging between 55.0 and 108.1 mg/kg (averaging 79.4 mg/kg) is above the NOAA, TEL, PEL and SLG limits. However, the mean value of Cr is above the medium value of worldwide soils (11–22 mg/kg) but lower than CSC ranges. The average abundance of Cr in the earth's crust is 100 mg/kg. Cr compounds are widely used in pigments, paints and fungicides and may have been leached to KTD through Zarqa River or other wastewater treatment plants. In addition, Cr may leach from nearby soil profiles, where Al-Ghazzawi (2010) reported an average of 98.91 mg/kg in soils of KTD upstream catchment. Low to moderately positive correlations were found between Cr and clay content, TOM, $CaCO_3$, pH, CEC, Fe, K, Sr, Cd, Cu, Pb, Co and Cl (Appendix 2 of ESM).

Ni is an essential trace element for plants and animals. Ni concentrations in KTD bottom sediments varied from 11.0 to 77.0 mg/kg, with an average level of 42.6 mg/kg. The average Ni content is lower than the SLG (of 75 mg/kg) and the CSC range (100 mg/kg) (Maiti 2003) (Table 2). High positive correlations between Ni and clay content, TOM and CEC were observed (Appendix 2 of ESM). With respect to Mendil et al. (2010) study, the average nickel values (79.2 mg/kg) exceeded both the TEL and PEC values for nickel (Table 1).

Based on the trace metals concentrations, KTD sediments could be a potential fertilizer supplement and soil conditioner, enhancing and restoring the eroded and poor soils in Jordan (if other parameters are supporting this assumption).

Index of geoaccumulation

The principles of geoaccumulation index were explained in Muller (1969). The basic statistics of I_{geo} calculations for trace metals are listed in Table 1. These results were compared to Muller scales (1981) and indicated that KTD sediments are unpolluted with Mn, Sr, Cu, Ni, Cr and Fe ($I_{geo} = -0.63, -0.58, -0.35, -0.24, -0.23$ and -0.2, respectively), but unpolluted to moderately polluted with Zn, Pb and Co ($I_{geo} = 0.42, 0.41$ and 0.06, respectively). However, KTD sediment is moderately polluted with Cd ($I_{geo} = 1.6$). On the basis of mean I_{geo} values, using average crustal abundance as background value, I_{geo} of trace metals were ranked in the following order: Cd > Pb > Zn > Co > Cr > Ni > Fe > Cu > Sr > Mn (Table 1).

Enrichment factor

The EF is a useful indicator to distinguish the sources of metal contents in sediments. The EF calculations have been explained in Ergin et al. (1991). According to Zhang and Liu (2002) and Zheng et al. (2008), EF values ranging between 0.5 and 1.5 indicate that the metal is entirely from natural processes, whereas EF values greater than 1.5 are more likely to be of anthropogenic origin.

The average EF values of Cd, Zn, Co and Pb are greater than 1.5 (Table 1), suggesting that they have been probably originated from anthropogenic (and partially natural) sources. Fe, Sr, Cu, Ni and Mn are of natural origin as their average EF values are less than 1.5. Trace metals were ranked in the following order: Cd > Zn > Pb > Co > Cr > Ni > Cu > Sr > Mn. Other authors as Yalcin et al. (2008) concluded that heavy metal accumulation in the sediments of creek Nigde, Turkey, is believed to be derived from geogenic sources and not from nearby operated Sb-Hg–W-Fe quarries.

Degree of contamination

Based on Sutherland (2000) classification for determining the degree of trace metal contamination of sediments, we can classify the degree of metal contamination of KTD sediments as deficient to minimal enrichment for Mn, Cu, Ni, Sr and Co, but moderately enrichment factors for Zn and Pb. However, KTD sediments are extremely high-enriched in Cd.

Partition coefficients (K_d)

The K_d is the ratio of the concentration of an element on a solid phase (sediment) divided by the equilibrium concentration in the contacting liquid phase (water) (Balls 1989). The average K_d for metals in water soluble extracts to sediments was calculated from the ratio between the total abundance in sediments and total concentrations in reservoir water (Table 3).

$$K_d = \log\left[\text{Me}_{(Sed)}/\text{Me}_{(W)}\right],$$

where K_d = coefficient of distribution, $\text{Me}_{(Sed)}$ = metal concentration in sediments, $\text{Me}_{(W)}$ = metal concentration in water extracts.

K_d is useful for predicting element behavior and movement between the water and sediments, which vary widely depending on physicochemical properties (especially TOM and clay content).

Trace metals in KTD dam sediments generally exhibited K_d values ranging between 3.12 (for Cu) and 6.12 (for Fe) (Table 3). These high values indicate that the metals affinity for sediments is high (i.e., retained by the sediment through sorption reactions, where the contents of clay and TOM are high). Metals with lower K_d migrate readily, resulting in environmental concentrations that fluctuating more smoothly and rapidly and is available for transport. These results suggest that trace metals in KTD sediments have low tendency to move to the liquid phase (reservoir waters) with potentially low levels of negative impacts on water quality.

Table 3 Average distribution coefficient (K_d) of selected trace metals on KTD sediments

Metal	Concentration of metal in sediments (mg/kg)	Concentration of metal in water (mg/l)	K_d (kg/l)
Cd	17.85	0.00557	3.5
Cr	79.37	0.02701	3.6
Cu	30.26	0.02245	3.12
Fe	44,445.5	0.03351	6.12
Mn	275	0.00422	4.81
Pb	76.46	0.018205	3.62
Zn	373.51	0.006265	4.74
Ni	59	0.040955	3.16
Co	33	0.005605	3.77

Conclusion

Sediment samples from KTD bed have shown high Cd, Zn, Co and Pb content among 10 studied trace metal, but the values of Fe, Cr, Cu, Mn, Ni and Sr are under the permissible limit of sediment quality guideline. Percentage of TOM, Clay and CEC showed positive correlation with trace metal content of sediments which signifies that there is higher metal association with TOM and clays.

The average grain size of KTD bottom sediments of 0.006 micron indicates a very fine nature (silt-clayey). The level of TOM content in KTD sediments was high with averages of 7.0%. The pH level in KTD sediments was slightly alkaline. The mean CEC values for KTD were within the medium to high range (100.5 meq/100 g). Mineralogical study showed that the bottom sediments of KTD are primarily composed of quartz, calcite, feldspars and dolomite, with an average content of carbonates of 35.5%. XRD and SEM study revealed the presence of kaolinite, illite, chlorite, montmorillonite and smectite. TOM, pH, CEC and CO_3 values varied spatially with higher values coincided with very fine fractions and lower levels associated with coarser sediment fractions.

(I_{geo}) between trace metals in the KTD sediments produced the following outputs: Cd > Pb > zn > Co > Cr > Ni > Fe > Cu > Sr > Mn.

(EF) values of trace metals were ranked in the following order: Cd > Zn > Pb > Co > Cr > Ni > Cu > Sr > Mn.

Dredge of clayey silty facies sediments in KTD sediment could be used a source of artificial soils, while sandy facies sediment could be used as soil conditioner.

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