Interaction dynamics between a contaminated dredged sediment and extracting solutions of different nature

Nieves Garcia-Blas^{1,2} & Eva Jimenez-Relinque¹ & Roman Nevshupa¹ & Marta Castellote¹

Abstract

Purpose The purpose of this work is to study the dynamics between the matrix of a contaminated marine sediment, its contaminants and various desorbing solutions by means of equilibrium tests, sedimentation trials and zeta potential, with the focus on assessing optimum enhancing solutions for decontamination purposes.

Materials and methods The sediment samples were analysed to determine their physico-chemical characteristics: particle size distribution, solids concentration, total organic carbon (TOC), content of heavy metals, organic contaminants, mineralogical phases, zeta potential and buffer capacity. Twelve extracting solutions of different nature were used for equilibrium tests, in which the dynamic behaviour of the sediment was evaluated. Elemental analysis was carried out for the sediment samples and the solutions before and after the tests.

Results and discussion The sediment was mainly composed of clay and lime, with a high content of iron, which has a strong influence on sorption-desorption processes. The sediment had a considerable buffer capacity at low and high pH values. The desorption of the metals was not proportional to pH. The highest decrease in the concentration of metals from the sediment was obtained with 0.2 M ethylenediaminetetra-acetic acid (EDTA) and 1 M nitric acid, while the lowest degree of metal extraction occurred in pure water and potassium iodide (KI).

Conclusions The most important parameters for contaminant release were complexation ability of the solution for the sediment components and pH of the solution. A promising design for the remediation treatment for the investigated sediment includes complexation and strong acid agents.

Keywords Dredged sediment chemistry · Extracting solutions · Sediment decontamination · Sedimentation rate · Zeta potential

1 Introduction

Marine sediments dredged from harbours are usually heavily contaminated with a wide variety of pollutants, such as heavy metals and organic compounds. Contamination has a profound impact on the reutilization of marine sediments and contributes to a loss of biodiversity, degradation of the ecosystems and a risk for humans (Eggleton and Thomas 2004; Zhang et al. 2014). Therefore, proper management of sediments is needed in order to implement the EU Water Framework Directive (Den Besten et al. 2003). Despite several decades of research, an efficient technology for sediment decontamination has not yet been developed. For this purpose, one of the most important problems is the lack of knowledge of the dynamics of a sediment matrix–contaminants–solutions system.

So far, most of the research on dynamics of this system has been focused on soils, while the dredged sediments have not been sufficiently addressed. Even though most aspects of research for soils can be applied for dredged marine sediments, the latter have specific characteristics, such as moisture and different salts content. In addition, dredged sediments are usually contaminated with a complex mixture of pollutants of different nature. Specifically for sediments, the report from Förstner and Salomons (2010) is worth mentioning, since it is about the first decade of the EU Water Framework Directive (WFD) and the European sediment research network, SedNet (Brils and de Deckere, 2003). Research and management issues were addressed in the four volumes of the SedNet books “Sustainable Management of Sediment Resources” (Barceló and Petrovic 2007; Bortone and Palumbo 2007; Heise 2007; Owens 2008). The literature (Apitz and Power, 2002; Förstner et al. 2004; Owens et al. 2005; Apitz et al. 2007; Brils 2008; Casado-Martínez et al. 2009; Obhođaš and Valković, 2010; Vdović et al. 2010; Romano et al. 2013; Apeti and Hartwell 2016) deals mainly with characterisation and management of the sediments. There have been fewer studies focused on the remediation technologies for dredged sediments (Ferdinandy-van Vlerken 1998; Poletini et al. 2006; Peng et al. 2009; Rozas and Castellote 2012; Pazos et al. 2013; Pedersen et al. 2015; Rozas and Castellote 2015). Mulligan et al. (2001) revised the developed methods evaluating their applicability, limitations and cost. Others reviewed the state of the art on electrochemical remediation of polluted soils, sediments and groundwater (Reddy and Cameselle 2009; Ribeiro et al. 2016). The fact that the organic and inorganic contaminants may simultaneously adsorb on the soil particle surface, organic matter of the sediment or precipitate as a different solid phase are the main obstacles in this study and in the development of an efficient remediation technology. Both sorption/desorption and precipitation/dissolution depend on the type of contaminant, its concentration, type of soil, surface characteristics of soil, chemistry of pore fluid and pH of the soil. In most cases an extracting agent must be used to remove organic and inorganic contaminants (Reddy and Cameselle 2009) through sorption-desorption reactions and by controlling the basic properties (Reddy and Dunn 1986; Landner 2006). On the basis of a literature review (Shaheen et al. 2013), the main parameters of the soil that control adsorption and desorption of contaminants are pH, redox potential, cation exchange capacity (CEC) (fine soils present higher CEC), clay fraction (< 0.02 mm), organic matter and Fe, Al and Mn oxyhydroxides. It is important to remark the role of the surface charge of the particles of the sediment—the zeta potential (Yeung et al. 1997; Yukselen and Kaya, 2003; Castellote et al. 2010; Hunter 2013; Rozas and Castellote 2015). All these parameters can be controlled by extracting solutions. Even though previous studies addressed some of the aspects of controlling of heavy metal extraction by different desorbing agents (Nystroem et al. 2006; Rozas and Castellote 2012), the dynamics between the contaminants and the sediment has not been studied so far. The purpose of this work is to study the dynamics between the matrix of a contaminated marine sediment, their contaminants and various desorbing solutions by means of equilibrium tests, sedimentation trials and zeta potential with the focus in assessing optimum enhancing solutions for decontamination purposes.

2 Materials and methods

Samples of a dredged contaminated sediment were obtained from a European port in February 2018. The exact location of the port cannot be revealed due to confidentiality reasons. To preserve the organic fraction, the sediment samples were stored in hermetic plastic bags and frozen at -20°C .

The dredged sediment samples were fully characterised using the following techniques: size particle distribution (dry sieving), solids concentration, total organic carbon (ISO 10694), content of heavy metals by X-ray fluorescence (XRF), amount and type of organic contaminants using Gas chromatography–mass spectrometry (GC-MS), Fourier transformed infrared spectrometry (FTIR) and X-ray diffraction (XRD). XRD was carried out with radiation $\text{CuK}\alpha$ (40 kV, 30 mA). A Zeta Meter 3.0+ was used to determine the zeta potential for 0.1 g of sediment suspended in 100 ml of deionized water. Equilibrium tests were performed to determine the dynamics of twelve different solutions with the sediment. The first eight solutions—test 1: deionized water; test 2: 1 M nitric acid; test 3: 1 M sodium hydroxide; test 4: 0.2 M citric acid; test 5: 0.5 M acetic acid; test 6: 0.2 M oxalic acid; test 7: 0.2 M ethylenediaminetetra-acetic acid (EDTA); and test 8: 0.2 M potassium iodide—were used as typical enhancing solutions in remediation experiments for heavy metals. The last four

solutions, test 9 to 12, were commercial non-ionic surfactants. The tests were conducted using 9.5 ± 1.5 g of sediment, and 29.5 ± 3.5 g of the extracting solution. The suspension was agitated during 2–3 days at room temperature, and then the solid phase was filtered out using 5- μm syringe filters. Sedimentation was measured using a camera and a chronometer after 30 min of agitation, by measuring the level of the solid-liquid interphase. After the treatments, the sediment samples were characterised by XRD and XRF. The calibration material for XRF was the same for all the samples without taking into account different matrix effects. The metal concentration in the solutions was analysed by inductive-coupled plasma optical emission spectrometry (ICP-OES). Chemical bonds in the initial sediment samples and in the samples treated by the solutions 9–12 (surfactants) were analysed using FTIR in mid-IR range 400–4000 cm^{-1} . Liquid samples were characterised using attenuated total reflection (ATR) in the range 525–4000 cm^{-1} with spectral resolution 1 cm^{-1} .

3 Results and discussion

The results of the initial characterisation of the sediment are given in Table 1. The particle size of the sediment showed that the largest fraction (67% by mass) was $\leq 63 \mu\text{m}$ and almost 30% was $\leq 2 \mu\text{m}$.

The results from the XRD analysis of the untreated sediment, which was dried at 100 °C during 24 h, indicated that the main mineral phase was quartz (SiO_2) followed by silicates: muscovite, $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$; pyroxene, MgO_3Si ; and pigeonite, $(\text{Ca,Mg,Fe})(\text{Mg,Fe})\text{Si}_2\text{O}_6$, and a small amount of clay minerals such as illite, smectite, montmorillonite and kaolinite. Iron-containing minerals including magnetite and gupeite (Fe_3Si), humic acid organic material and halite (NaCl) were also found. After the calcination of the sediment at 1000 °C, the characteristic peaks of magnetite vanished, while new lines corresponding to hematite appeared. No peaks corresponding to heavy metals could be detected. It can be concluded that the sediment was mainly composed of clay and limes, with a high Fe content, which has a strong influence on sorption-desorption processes.

The FTIR spectra of the untreated sediment sample showed strong and medium bands, which are typical of a mineral soil and coordinated hydroxyl groups) (Kloprogge 2016; Madejová et al. 2017). Two groups of weak bands at 2854–2975 cm^{-1} and 1358–1514 cm^{-1} were ascribed to stretching and bending vibration modes of aliphatic structures (Rusanov et al. 2015).

The zeta potential (ζ -potential) of the sediment was close to zero at pH values around 2, and it linearly increased with increasing pH until pH 11, when ζ -potential reached -30 mV (see Fig. 1a). At pH values higher than 11, the ζ -potential was slightly less negative: -20 mV at pH 13. This behaviour was attributed to the dissolution of some components of the sediment, e.g. Al, in highly alkaline solutions. The XRF results described below support these findings. Fig. 1b shows that the sediment had a considerable buffer capacity at low and high pH, being very high in the ranges of pH 11–14 and 0–3.

Table 1 Initial characterization of the sediment

Parameter	Concentration
Metal (mg kg^{-1} d.w.)	
Arsenic	224.9
Cadmium	< 75
Chromium	< 50
Copper	2228.8
Lead	317.5
Nickel	47.1
Zinc	2897.8
Mercury	<19.4
Organic compounds (mg kg^{-1} d.w.)	
Total organic carbon	21,000
Total TPH C10-C40	70
Tributyltin (TBT)	57
Total PAH	< 0.30
Total PCB	< 0.0070
CaCO_3 (g kg^{-1})	10.2
Solids concentration (mass %)	33
Agglomerated mass (g)	0
Dry matter (mass %)	34.85
Microtox solid phase test (g l^{-1})	> 16
M 63 μm	203
Grain size (μm)	Mass %
< 2000	76.9
< 1400	76.8
< 1000	75.9
< 710	75.2
< 600	75.2
< 500	74.5
< 355	74.5
< 250	73.2
< 180	71.5
< 125	69.2
< 63	67.0
< 2	29.4

Fig. 1 a Zeta potential and b buffer capacity of the sediment as function of the pH

The sedimentation kinetics is shown in Fig. 2. All data sets could be adjusted reasonably well by a single exponential decay function. The solutions were ranked according to the sedimentation rate in the following order: EDTA > oxalic acid > acetic acid > NaOH $\approx$ citric acid > HNO₃ > KI > water, which can be linked with the complexing ability of the solution and the soil components. Suspensions 1 and 8 formed precipitates whose volume decreased due to rearrangements, and the supernatant solution got clearer, which suggested the formation of a flocculated sediment (Shaw 1966). Tests 3 and 5 turned the solution reddish, which was attributed to Fe(OH)₆³⁻ and iron acetate, respectively. Tests 2, 4 and 6 left the solution yellowish, which was ascribed to the basic species as Fe(OH)₂²⁺ and Fe(OH)₂⁺ (Arribas Jimeno et al. 1992). In test 7 the sediment particles did not settle after 237 min. Regarding the sedimentation tests performed with surfactants, in tests 10 and 12 the solution turned yellowish, while in tests 9 and 11 it remained colourless.

The XRD results of the sediment samples after the equilibrium tests showed a significant decrease in the diffraction lines of gupeite and halite in all samples. The line for the compound (C₁₇H₁₇NO₂) around $\theta = 22^\circ$ appeared in the spectra after the tests 4 (citric acid), 8 (KI) and 9 (non-ionic surfactant A). For the solutions 3 (NaOH) and 6 (oxalic acid), flakeite (K₃Ca₂Na)[A₁₈Si₈O₃₂] $\cdot$ 12H₂O and browneite (Ca_{0.002} Fe_{0.01} Mn_{0.993} S) were observed. In samples 4, 6 and 8, albite (NaAlSi₃O₈) was also detected.

The results of XRF analysis supported that the sediment treatments with various extracting solutions caused changes in metal concentrations in the solutions as well as in both metal and non-metal concentrations in the sediment samples. The most relevant results are the following: the percentages of the elements relevant to adsorption and desorption, i.e. Na, Cl and S, decreased in all samples with the exception for Na in solution 3. In tests 2 (nitric acid) and 7 (EDTA), the concentrations of metals Mg, Ca, Al and Fe significantly decreased, which was attributed to dissolution of clays in strong acid (test 2) and to the complexation by EDTA (test 7). Significant decrease of Si concentration in the sediment samples was observed in tests 4, 5 (acid solutions) and 7 (EDTA). In the latter, it could be due to complexation of ion compounds. In contrast to the elements mentioned above, Mg concentration rose in the sediment samples in tests 3 and 11. Mg, Ca and Fe increased in tests 3 and 6, in agreement with the results of XRD.

The results from FTIR did not reveal any variation in the bands assigned to the mineral soil, but the bands assigned to organic components slightly varied. In the case of surfactant 9, the organic bands decreased, while for the surfactants 10–12 an increase was detected. In the test with surfactant 12, two sharp bands at 2854 cm^{-1} and 2924 cm^{-1} , corresponding to symmetric and asymmetric stretching of methylene groups as well as a weak ester carbonyl band at 1732 cm^{-1} , were noticed. These results suggest that surfactant 12 (polyoxyethylenesorbitan monolaurate) containing methylene, ether and ester groups strongly adsorbed on the sediment. The bands of Zn-, As-, Ni- and Cu-oxy compounds were not identified in the FTIR spectra (Goldberg and Johnston 2001; Balamurugan et al. 2002; Khan et al. 2016).

The decrease of the percentage of Ni, Cu, Zn, As and Pb in the sediment samples, measured using XRF after the equilibrium tests, is shown in Fig. 3. It should be stressed that the sample mass could have changed during the tests; therefore, the results cannot be used for tracking the variations of absolute quantities of elements. In fact, in some cases negative variations of elemental concentrations, i.e. their apparent increase, were observed. This should be interpreted as the decrease of the total sample mass due to dissolution or suspension of the bulk of the sediment, but not to deposition of metals from the solution to the solid phase. These results point at a pronounced removal of organic matter by the four surfactants. In most of the tests, the pH of the solution increased during the trial (Fig. 3), which is an indicator of the dissolution of basic compounds of the sediment.

Fig. 2 Evolution of the liquid-solid interphase in the sedimentation processes

In test 1, with distilled water, the concentration of metals decreased only slightly. Ni^{2+} is a slightly acid cation whose hydroxide precipitates at $\text{pH} \geq 7$ (Arribas Jimeno et al. 1992). Thus, the concentration of Ni did not decrease in any solution at $\text{pH} \geq 7$. Solution 2, which was extremely acid, is the only one in which the concentration of all metals decreased. The metals were ranked according the degree of their removal from the sediment in test 2: Cu and Zn ($> 90\%$) $>$ Pb $>$ Ni $>$ As. In highly basic media, the amphoteric compounds Cu, Zn and As were extracted to the solution. The concentration of Ni and, Pb in the sediment samples increased even though Ni is the only hydroxide that is not soluble in excess of alkalis (Arribas Jimeno et al. 1992). All the metals decreased in citric acid with the exception of Pb, showing a clear increase. This indicates that Pb is in the form of Pb^{4+} , which does not form complexes with citrate. Acetic acid released Cu, Zn and Pb as Ac-metal complexes. Oxalic acid did not have a significant impact, with Cu and Zn as the metals whose concentrations decreased to a larger extent. In the test with EDTA, all metals were extracted from the sediment with the exception of Pb, with Cu and Zn as its most significant extractions. In the test with KI, the metal extraction degree was very low. In the tests with surfactants, the concentrations of all metals seemed to increase, which implies a loss of the total mass (dissolution of amorphous organic matter) of the sediment samples. Finally, it should be highlighted that Zn, with the exception of surfactants, was extracted in all tests since its hydroxide precipitates from the solution at pH values around 7.5 and it has an amphoteric character.

Before getting deeper into the discussion of these dynamics, it should be reminded that sorption depends on the soil, on the characteristics of the contaminants and on the competition between them for the sediment sites (Covelo et al. 2007; Shaheen 2009; Shaheen et al. 2013). The sorption's strength is not the same when a soil or sediment has been spiked with the contaminants or if contamination has been there for years, as is the case of the sediment of this research. When an enhancing solution is added, the chemistry of the sediment is completely changed and then, desorption is controlled by the characteristics of the extracting agent. To analyse the sorption ability of different species on a substrate, the distribution coefficient, K_d , which is defined as the ratio of the concentration of an element in the solid phase (mg kg^{-1}) to that in the equilibrium solution after a specified reaction time (mg l^{-1}), was calculated and normalised for each system (Fig. 4). The different metals were ranked for each test according to their K_d as follows: 1: Cu > Zn; 2: As > Ni > Pb > Zn > Cu; 3: Pb > Ni > Zn > Cu; 4: Pb > Ni > As > Cu > Zn; 5: As > Pb > Ni > Cu > Zn; 6: Pb > As > Ni > Cu $\approx$ Zn; 7: Ni > Pb > As > Cu > Zn; 8: Zn > Cu > As.

Fig. 3 Decrease in metal concentrations in the sediment samples after the equilibrium tests. The negative part of the plot is shown until - 75%. The value of the bar for Pb in NaOH is - 165%. Negative values are assigned to dissolution of solid phases of the bulk of the sediment. The table shows the values of initial and final pH of the solutions

Three key characteristics of the metals are identified as the most influential towards the K_d (Shaheen 2009; Shaheen et al. 2013): (1) The hydrolysis constants (Baes Jr and Mesmer, 1981; Barnum 1983; Raposo et al. 2002). Metal ions in aqueous solutions form mononuclear and polynuclear hydroxy-complexes. The lower the constant of hydrolysis, the stronger the specific element sorption. Additionally, multivalent cations are very prone to hydrolysis and free metal ions are never the majority species when pH is greater than the first hydrolysis constant (Kinraide 2009). Therefore, the theoretical decreasing order of sorption based on hydroxyl-complexes formed would be Pb (7.8) > Cu (7.96) > Zn (8.96) > Ni (9.86) > As (11.51). (2) Ionic radius. The smaller the radius, the higher the tendency to be swelled by cationic exchange (Sposito 2008) (nm). Then, Pb (0.084-0.12) > Zn (0.074) > Cu (0.072) > Ni (0.069) > As (0.056-0.058). (3) Misono softness value: Classification of ions as hard and soft and quantification of their character were developed by Pearson (Pearson 1963). Hard ions are less polarized when chemically bound and have higher resistance to deformation of their electron cloud, which implies a tendency of forming ionic bonds. Soft ions are more polarized and have lesser resistance to deformation of their electron cloud, tending to form covalent bonds (Pearson 1963; Ownby and Newman 2003). Therefore, the Misono softness parameter is an index of the tendency of the species to form covalent bonds with colloids, and depends on the ionic charge and the ionization potential. Pb (borderline acid, 3.58) > Cu (borderline acid, 2.89) > Ni (borderline acid, 2.82) > Zn (borderline acid, 2.34), As (hard acid).

From the comparison of the rankings of K_d s obtained in this research for the different solutions and the theoretical tendencies in function of the characteristics of the metals, and being the same sediment for all of them, it is clear that the characteristics of the solutions are most relevant. On one hand, sedimentation tests allowed to determine the amount of solid matter dissolved or suspended into the solutions, mainly related to the complexing ability with the soil components that, at the same time, influences the release of metals whose sorption is much related to formation of complex with amorphous oxides of Fe, Al and organic

matter.

Concerning the pH of the solutions, the ranking of pH at the end of the trials was $\text{NaOH} \gg \text{SurfB} \approx \text{SurfC} \approx \text{Water} \approx \text{SurfD} > \text{EDTA} > \text{Oxalicacid} > \text{AcAcid} > \text{CitAcid} \gg \text{HNO}_3$. In general, sorption of metals increases as the pH decreases. In this sediment, desorption of the metals is related but not proportional to pH. Therefore, it could be said that in order to design a remediation treatment for this sediment, a combination of complexation and acid media seems to be the optimum setup.

4 Conclusions

The dynamics of the interactions between a contaminated dredged sediment from a harbour and different extracting solutions have been carried out, with the focus on the design of optimum remediation processes. It can be derived that the global results of desorption of contaminants with enhancing solutions for a particular system cannot result from the theoretical expected behaviour of just considering individual aspects. Several processes have to be taken into account; mainly, the complexation ability for the sediment components (organic matter, Al and Fe in the matrix) and pH of the solution (dissolution of mineral phases, decrease of the zeta potential of the double layer impeding reabsorption of cations).

Fig. 4 Normalised K_d (in arbitrary units) for each solution. Missing bars in the graph mean that the value of the metal in the solution was below the limit of detection of the analytical technique

Accordingly, the best results for this sediment were reached using EDTA and strong acid solutions.

Funding information The authors want to acknowledge the support of the Community of Madrid through the program “Garantía Juvenil” for the doctoral grant of the first author of this research.

References

- Apeti DA, Hartwell SI (2016) Baseline assessment of organic contaminants in surficial sediment from Kachemak Bay, Alaska. *Reg Stud Mar Sci* 7:196–203
- Apitz SE, Power EA (2002) From risk assessment to sediment management an international perspective. *J Soils Sediments* 2:61–66
- Apitz SE, Barbanti A, Bernstein AG, Bocci M, Delaney E, Montobbio L (2007) The assessment of sediment screening risk in Venice Lagoon and other coastal areas using international sediment quality guidelines. *J Soils Sediments* 7:326–341
- Arribas Jimeno S, Burriel Marti F, Hernandez Mendez J, Lucena Conde F (1992) Química analítica cualitativa. Paraninfo
- Baes CF Jr, Mesmer R (1981) Thermodynamics of cation hydrolysis. *Am J Sci* 281:935–962
- Balamurugan B, Mehta BR, Avasthi DK, Singh F, Arora AK, Rajalakshmi M, Raghavan G, Tyagi AK, Shivaprasad SM (2002) Modifying the nanocrystalline characteristics—structure, size, and surface states of copper oxide thin films by high-energy heavy-ion irradiation. *J Appl Phys* 92:3304–3310
- Barceló D, Petrovic M (eds) (2007) Sustainable management of sediment resources. Sediment quality and impact assessment of pollutants. Elsevier, Amsterdam
- Barnum DW (1983) Hydrolysis of cations. Formation constants and standard free energies of formation of hydroxy complexes. *Inorg Chem* 22:2297–2305
- Bortone G, Palumbo L (eds) (2007) Sustainable management of sediment resources. Sediment and dredged material treatment. Elsevier, Amsterdam
- Brils J (2008) Sediment monitoring and the European water framework directive. *Ann Ist Super Sanita* 44:218–223
- Brils J, de Deckere E (2003) SedNet—an evolving network aimed at sustainable sediment management. *J Soils Sediments* 3:127–128
- Casado-Martínez M, Forja J, DelValls TA (2009) A multivariate assessment of sediment contamination in dredged materials from Spanish ports. *J Hazard Mater* 163:1353–1359
- Castellote M, Botija S, Andrade C (2010) Assessment of electrophoresis and electroosmosis in construction materials: effect of enhancing electrolytes and heavy metals contamination. *J Appl Electrochem* 40:1195–1208
- Covelo EF, Vega FA, Andrade ML (2007) Simultaneous sorption and desorption of Cd, Cr, Cu, Ni, Pb, and Zn in acid soils: I. Selectivity sequences. *J Hazard Mater* 147:852–861
- Den Besten PJ, De Deckere E, Babut MP, Power B, DelValls TA, Zago C, Oen AM, Heise S (2003) Biological effects-based sediment quality in ecological risk assessment for European waters. *J Soils Sediments* 3:144–162
- Eggleton J, Thomas KV (2004) A review of factors affecting the release and bioavailability of contaminants during sediment disturbance events. *Environ Int* 30:973–980
- Ferdinandy-van Vlerken MA (1998) Chances for biological techniques in sediment remediation. *Water Sci Tech* 37:345–353
- Förstner U, Salomons W (2010) Sediment research, management and policy. *J Soils Sediments* 10:1440–1452
- Förstner U, Heise S, Schwartz R, Westrich B, Ahlf W (2004) Historical contaminated sediments and soils at the river basin scale. *J Soils Sediments* 4:247–260
- Goldberg S, Johnston CT (2001) Mechanisms of arsenic adsorption on amorphous oxides evaluated using macroscopic measurements, vibrational spectroscopy, and surface complexation modeling. *J Colloid Inter Sci* 234:204–216
- Heise S (ed) (2007) Sustainable management of sediment resources. Sediment risk management and communication. Elsevier, Amsterdam
- Hunter RJ (2013) Zeta potential in colloid science: principles and applications. 2nd edn. Academic press
- Khan MF, Ansari AH, Hameedullah M, Ahmad E, Husain FM, Zia Q, Baig U, Zaheer MR, Alam MM, Khan AM, AlOthman ZA, Ahmad I, Ashraf GM, Aliev G (2016) Sol-gel synthesis of thorn-like ZnO nanoparticles endorsing mechanical stirring effect and their antimicrobial activities: potential role as nano-antibiotics. *Sci Rep* 6:27689
- Kinraide TB (2009) Improved scales for metal ion softness and toxicity. *Environ Toxicol Chem* 28:525–533
- Kloprogge T (2016) Infrared and Raman spectroscopy of minerals and inorganic materials. In: Lindon J, Tranter GE, Koppenaal D (eds) *Encyclopedia of Spectroscopy and Spectrometry*, 3rd edn. Academic Press, London, pp 267–281
- Landner L (2006) Speciation of metals in water, sediment and soil systems: Proc Intern Workshop, Sunne. October 15–16(1986):11
- Madejová J, Gates WP, Petit S (2017) IR spectra of clay minerals. In: Gates WP, Kloprogge JT, Madejová J, Bergaya F (eds) *Developments in clay science*. Elsevier, Amsterdam, pp 107–149
- Mulligan CN, Yong RN, Gibbs BF (2001) An evaluation of technologies for the heavy metal remediation of dredged sediments. *J Hazard Mater* 85:145–163
- Nystroem GM, Pedersen AJ, Ottosen LM, Villumsen A (2006) The use of desorbing agents in electrodialytic remediation of harbour sediment. *Sci Total Environ* 357:25–37
- Obhodáš J, Valkovič V (2010) Contamination of the coastal sea sediments by heavy metals. *Appl Radiat Isot* 68:807–811
- Owens PN (2008) Sustainable management of sediment resources. Sediment management at the river basin scale. Elsevier, Amsterdam
- PN, Batalla RJ, Collins AJ, Gomez B, Hicks DM, Horowitz AJ, Kondolf GM, Marden M, Page MJ, Peacock DH, Petticrew EL, Salomons W, Trustrum NA (2005) Fine-grained sediment in river systems: environmental significance and management issues. *River Res Applic* 21:693–717
- Ownby DR, Newman MC (2003) Advances in quantitative ion character-activity relationships (QICARs): Using metal-ligand binding characteristics to predict metal toxicity. *QSAR Comb Sci* 22:241–246
- Pazos M, Iglesias O, Gómez J, Rosales E, Sanromán MA (2013) Remediation of contaminated marine sediment using electrokinetic-Fenton technology. *J Ind Eng Chem* 19:932–937
- Pearson RG (1963) Hard and soft acids and bases. *J Am Chem Soc* 85: 3533–3539
- Pedersen KB, Kirkelund GM, Ottosen LM, Jensen PE, Lejon T (2015) Multivariate methods for evaluating the efficiency of electrodialytic removal of heavy metals from polluted harbour sediments. *J Hazard Mater* 283:712–720
- Peng J-f, Song Y-h, Yuan P, X-y C, Qiu G (2009) The remediation of heavy metals contaminated sediment. *J Hazard Mater* 161:633–640
- Polettini

- A, Pomi R, Rolle E, Ceremigna D, De Propriis L, Gabellini M, Tomato A (2006) A kinetic study of chelant-assisted remediation of contaminated dredged sediment. *J Hazard Mater* 137:1458–1465
- Raposo JC, Sanz J, Zuloaga O, Olazabal MA, Madariaga JM (2002) The thermodynamic model of inorganic arsenic species in aqueous solutions: Potentiometric study of the hydrolytic equilibrium of arsenic acid. *Talanta* 57:849–857
- Reddy KR, Cameselle C (2009) *Electrochemical remediation technologies for polluted soils, sediments and groundwater*. John Wiley & Sons, Chichester
- Reddy MR, Dunn SJ (1986) Distribution coefficients for nickel and zinc in soils. *Env Pollut Series B, Chem Physical* 11:303–313
- Ribeiro AB, Mateus EP, Couto N (2016) *Electrokinetics across disciplines and continents*, 1st edn. Springer, Berlin
- Romano E, Bergamin L, Celia Magno M, Ausili A (2013) Sediment characterization of the highly impacted Augusta harbour (Sicily, Italy): modern benthic foraminifera in relation to grain-size and sediment geochemistry. *Env Sci Process Impact* 15:930–946
- Rozas F, Castellote M (2012) Electrokinetic remediation of dredged sediments polluted with heavy metals with different enhancing electrolytes. *Electrochimica Acta* 86:102–109
- Rozas F, Castellote M (2015) Selecting enhancing solutions for electrokinetic remediation of dredged sediments polluted with fuel. *J Env Manag* 151:153–159
- Rusanov A, Nevshupa R, Martin J-M, Garrido MÁ, Roman E (2015) Tribochemistry of hydrogenated amorphous carbon through analysis of mechanically stimulated gas emission. *Diam Relat Mater* 55: 32–40
- Shaheen SM (2009) Sorption and lability of cadmium and lead in different soils from Egypt and Greece. *Geoderma* 153:61–68
- Shaheen SM, Tsadilas CD, Rinklebe J (2013) A review of the distribution coefficients of trace elements in soils: influence of sorption system, element characteristics, and soil colloidal properties. *J Colloid Inter Sci* 201:43–56
- Shaw DJ (1966) *Introduction to colloid and surface chemistry*. 1st edn, Butterworth-Heinemann
- Sposito G (2008) *The chemistry of soils*, 2nd edn. Oxford University Press, Oxford
- Vdovič N, Obhodáč J, Pikelj K (2010) Revisiting the particle-size distribution of soils: comparison of different methods and sample pre-treatments. *Eur J Soil Sci* 61:854–864
- Yeung AT, C-n H, Menon RM (1997) Physicochemical soil-contaminant interactions during electrokinetic extraction. *J Hazard Mater* 55: 221–237
- Yukselen Y, Kaya A (2003) Zeta potential of kaolinite in the presence of alkali, alkaline earth and hydrolyzable metal ions. *Water Air Soil Pollut* 145:155–168
- Zhang C, Yu Z-g, G-m Z, Jiang M, Yang Z-z, Cui F, Zhu M-y, Shen L-q HL (2014) Effects of sediment geochemical properties on heavy metal bioavailability. *Environ Int* 73:270–281