Influences of riverbed siltation on redox zonation during bank filtration: a case study of Liao River, Northeast China
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ABSTRACT
The upper part of riverbed sediment is one of the key interfaces between surface water and groundwater, and biogeochemical process in this interface has a profound influence on the chemistry of infiltrated water. The lithology and permeability of bed sediment is mainly controlled by variation in river hydrodynamic conditions. However, there have been few studies of the effect of riverbed siltation on the hydrochemistry and redox reactions of infiltrated water due to the high variability in these processes and challenges associated with sampling. This study selected and examined a river channel near a site of riverbank filtration by drilling on the floating platform and conducting microelectrode testing and high-resolution sampling. The hydrodynamic and chemical characteristics of pore water in and lithologic characteristics of riverbed sediment, the siltation, and redox zone were examined and compared. Differences in hydrodynamic conditions changed the lithology of riverbed sediment, consequently affecting redox reactions during the process of river water infiltration. Variations in siltation changed the residence time of pore water and organic matter content, which ultimately resulted in differences in extension range and intensity of redox reactions. This study provides a valuable reference for understanding the effect of riverbed siltation on water quality of riverbank infiltration.

Key words | redox zonation, riverbed sediment, siltation, surface water-groundwater interaction

HIGHLIGHTS
- Riverbed siltation was examined by waterway drilling techniques.
- High-resolution sampling identified redox zoning under siltation.
- Riverbed siltation changed redox zoning at the river water–sediment interface.

INTRODUCTION
Surface water infiltration is an important category of surface water–groundwater interaction, and in particular, river bank filtration (RBF) increases groundwater recharge. RBF is widely used around the world as a sustainable source of drinking water (Ray et al. 2002; Tufenkji et al. 2002), as this technology reduces environmental problems resulting from overexploitation of water resources and alleviates water supply crises in some areas (Ray et al. 2003; Hu et al. 2016). RBF not only changes the hydraulic connection between the river and groundwater, but also dilutes the concentrations of pollutants as a large proportion of dissolved and suspended contaminants are removed from water during the infiltration process. The redox environment of sediment is changed due to the infiltration of
oxygen-carrying surface water, which is believed to promote redox reactions and the degradation and removal of pollutants (Romero-Esquivel et al. 2017; Guo et al. 2018). Developing appropriate management to realizing the full benefits of RBF requires an understanding of the evolution of hydrogeochemistry during riverbank infiltration (Henzler et al. 2016).

The riverbed sediment zone constitutes the uppermost zone during water infiltration, and this zone shows the greatest variations in physical, chemical, and biological gradients between river water and groundwater. These characteristics of the river sediment zone make it a key interface within surface water–groundwater interactions (Sophocleous 2002; McLachlan et al. 2017). The biogeochemistry of riverbed sediment plays a vital role in maintaining groundwater quality and ecological security (Tufenkji et al. 2002). During surface water infiltration, microbial fermentation, aerobic respiration, denitrification, iron–manganese reduction, sulfate reduction, and other reaction processes act to degrade bioavailable organic matter in riverbed sediment, resulting in sequential redox zonation (Yuan 2017). The permeability of sediment to water infiltration is influenced by physical, chemical, and biological factors, such as flow conditions, dissolved organic matter, and the activity of microorganisms (Brunke & Gonser 1997). Silation not only reduces riverbed sediment permeability and recharge intensity, but also changes the hydrodynamic conditions of bank infiltration, drives changes to environmental conditions at the sediment–water interface, and affects the evolution of biogeochemical reactions during infiltration (Brunke & Gonser 1997; Cardenas 2008; Smith & Lerner 2008; Hu et al. 2014). For example, the infiltration rate affects oxygen consumption within a certain range, with a low infiltration rate resulting in high oxygen consumption and an anoxic state. In addition, variation in river flow may affect the structure and function of the riverbed microbial community, thereby potentially impacting biogeochemical processes and water quality. Certain extreme weather conditions, such as inundation, also affect water quality of RBF (Ascott et al. 2016), as a shortened infiltration travel time under heavy rainfall can result in reduced removal of pathogens, heavy metals, suspended matter, dissolved organic carbon, and organic micropollutants during infiltration (Derx et al. 2013; Pazouki et al. 2016). Infiltration water residence time and redox condition are two main parameters determining the performance of RBF (Henzler et al. 2016). While some recent studies have reported on the effects of river morphology on hyporheic water exchange and the permeability of riverbed sediment (Zhang et al. 2017; Cheng et al. 2016), there remains a lack of research on the effects of river morphology on hydrochemistry. Past studies considered riverbed sediment to be a homogeneous and stable interface, ignoring the influence of factors such as scouring and silation on redox zonation during bank filtration.

The study area of the current study was a riverside well field in Shenyang, northeast China, in which groundwater quality is characterized to be of poor quality with high contents of iron and manganese. Previous studies have classified groundwater redox zones in different water flow paths during bank filtration by analyzing the spatial and temporal distribution of groundwater environmental indices and chemical components (Su et al. 2017). Dissolved organic carbon (DOC) and sedimentary organic carbon (SOC), as major electron donors, show high variability in sequential redox reactions under differences in microbial activities along the horizontal and vertical flow directions (Su et al. 2018; Yuan et al. 2020).

The Liao River is a highly seasonal river, with low flow periods characterized by silation of the channel, whereas incoming water flow and sediment concentration increase greatly during the flood period, resulting in an increase in the sediment transport capacity of the channel, channel scouring, and over-bank siltation. Water flow gradually reduces subsequent to the flood, with a concurrent decrease in the ability of water to carry sediment, resulting in a return to channel silation conditions. Previous studies have shown that rivers under the influence of upstream runoff and a downstream reservoir show obvious seasonal scouring and a decrease in the permeability of bed sediment, resulting in a variability in bed sediment depth of as much as 10 cm (Hu et al. 2007; Huang 2014). Porewater concentrations of Fe, Mn, and As far exceed drinking water standards, and changes in concentrations of these elements in porewater are related to the silation and scouring of bed sediment. The objectives of the present study were to: (1) analyze the spatial structure characteristics of the riverbed sediment of the Liao River; (2) identify differences in infiltration
permeability of sediment within a transverse segment of the river; and (3) analyze the spatial distribution of pore water chemical components and identify variation in redox zoning of scoured and silted riverbed sediment.

STUDY AREA AND METHODS

Study area

The study area of the present study is located 40 km north of Shenyang, northeastern China (Figure 1), and is situated on an alluvial plain in the middle and lower reaches of the Liao River. The study area has a river accumulational landform geomorphic type, comprising mainly low floodplain with a surface elevation varying between 42.0 and 52.0 m above sea level. The study area falls within a temperate subhumid monsoon climate zone, with an annual average rainfall and potential evaporation of 635.5 and 1,594 mm, respectively. The study area falls between the Tieling and Ma Hushan hydrological stations 27 and 20 km upstream and downstream, respectively, and the study area river reach has a width of ~250 m. Hydrologic observations of the study area indicate that water level and river discharge show clear seasonal variations, with maximums occurring in August and September and the flood period extending from June to October (Figure 2).

Geophysical exploration conducted in a previous study (Su et al. 2017) showed strong heterogeneity in the riverbed sediment (Figure 3). The sediment within the study area within the range of 22 m of the south bank and 14 m of the north bank of Liao River shows homogeneous characteristics with obvious stratification and low permeability. In contrast, sediment located in the middle of the riverbed showed high lateral variability and high permeability (Su et al. 2017). Grain size of sediment in the study area showed large variation, with sediment types including clay, silt, and sand. The uppermost layer of sediment of the south bank of ~0.5 m depth comprised silt. Surface silt thickness gradually decreased from the south bank to the main channel, and the surface silt thickness of the riverbed at the main channel ranged between 0 and 0.1 m.

Groundwater in the study area is stored in unconsolidated phreatic Quaternary aquifers over impermeable Tertiary glutenite, with Liao River being the main source of groundwater recharge. The aquifer is overlaid with loam and clayey soil with a thickness of ~50.0 m consisting of fine sand, medium-coarse sand containing gravel, sand,
gravel and pebble, and coarse sand containing gravel. Ten pumping wells are distributed in the study area, with the cumulative yield of the pumps remaining stable for many years at $\sim 30,000$ m$^3$ d$^{-1}$, resulting in several depression cones (Figure 1). The occurrence of two types of typical groundwater flow paths due to exploitation have been noted, namely shallow and deep flow paths. Groundwater flow along the shallow path through the silt layer flows at a slower rate of $\sim 13.5$ m d$^{-1}$ and has a long travel time. In contrast, the deep water flow path is characterized by good permeability and fast-flowing water, and has a closer hydraulic connection with river water (Su et al. 2014). The infiltration of river water from the Liao River into the groundwater acts as a vital water resource that is characterized by stable and good water quantity and quality.

Sampling and analysis

The riverbed section labeled ‘I–I’ (see Figure 1(c)) across the Liao River was selected as the control monitoring section in the present study as this section is consistent with the direction of the river infiltration and passes through the center of the groundwater drawdown funnel. Riverbed sediment and pore water samples were collected in September 2019 from the sampling locations shown in Figure 1(c).

For the collection of sediment samples, a mobile drilling platform was established over the Liao River and a portable high-frequency vibration drill (Wink S5 Vibracore, Canada) was used to collect sediment samples from a depth $\leq 5$ m below the riverbed (see Table 1). The collected undisturbed sediment was packed in polyvinyl chloride (PVC) pipe, which was cut into 0.5 m segments. The segments were sealed with sample plugs and sealing film and then placed in an air-tight box for storage in refrigerator at a low temperature. The samples were transported to the laboratory as soon as possible for analysis and testing (Figure 4).
River water samples were collected in sampling tubes through siphoning, which ensured that the surface layer of the sediment remained undisturbed. The physico-chemical parameters of each sample were measured, after which the sample was transferred to a clean polyethylene bottle, sealed with a protective agent according to the test requirements, stored at low temperature (4°C) and transported back to the laboratory for analysis and testing as soon as possible.

Pore water samples were collected from the upper 0–20 cm layer of sediment using an HR-Peeper sampler (High-resolution Peeper, Easy Sensor Ltd, China, Figure 4) (Xu et al. 2012). HR-Peepers were inserted into the sediment and retrieved after 48 h. Rhizon samplers (Rhizosphere Research Products, The Netherlands, Figure 4) were inserted into the sediment core through holes predrilled in the tube wall and pore water was collected from different depths below the 20 cm sediment layer using suction. During storage of pore water samples under refrigeration, the refrigerator was filled with nitrogen to avoid the influence of oxygen on subsequent tests.

Particle size distribution analysis was performed after sediment pretreatment through the use of screen analysis and a laser particle diameter analyzer (Bettersize2000, Dandong Better Instrument Co. Ltd, China). Microelectrodes (Unisense, Aarhus, Denmark) were used to measure oxidation–reduction potential (ORP), dissolved oxygen (DO), and pH of pore water samples. The accuracies of tests conducted were different at different sediment depths according to requirements, with precisions of 0.1 mm, 1, and 5 cm in the depth ranges of 0–1, 1–10, and 10–50 cm, respectively. Conventional anions (NO₃⁻, SO₄²⁻) in pore water were analyzed by ion chromatography (881-919 Compact IC, Metrohm, Herisau, Switzerland). Fe and Mn contents of pore water were measured by inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7500 C, Agilent Technologies Inc., USA).

**RESULT AND DISCUSSION**

**Structural and lithologic variation of riverbed sediment**

Changes in river hydraulic conditions result in cycles of scouring and siltation, which affect the porosity, permeability, and lithology of the riverbed. The present study revealed the characteristics and variability of siltation by comparing hydrodynamic conditions at different points of the control section and relating these to the spatial distribution of lithology.

**Hydrodynamic conditions**

Hydrodynamic conditions of a river segment are driven by drops in the height of the river upstream and downstream,
turbidity, and river channel morphology. A river flow rate that exceeds the threshold of bottom sediment critical transport velocity will result in the mobilization of bottom sediment and transport of this sediment downstream. The mobilization of bottom sediment will be enhanced during the rainy season due to higher river flows. This seasonal variation in hydrodynamic condition results in cycles of scouring and siltation of riverbed sediment, which in turn result in alternating changes in the permeability of the riverbed to water infiltration. Therefore, the river flow rate is an important index for quantifying hydrodynamic force. The river velocity and water depth at the monitored section were measured during September 2019 (Figure 5).

There were significant differences in hydrodynamic strength at the control section among the different sampling points along the cross-section, with the hydrodynamic strength of the north bank (concave bank) of the Liao River exceeding that of the south bank (convex bank), and the center of the riverbed showing the greatest hydrodynamic strength (HC7 point; river flow rate of 1.34 m s⁻¹). There was an obvious correlation between water depth and hydrodynamic condition, with the depth of water being positively related to the hydrodynamic intensity of the river. The riverbed section could be divided according to velocity and water depth into three zones of hydrodynamic intensity: (1) weak; (2) medium; and (3) strong (see Table 2).

| Hydrodynamic zoning | Flow rate (m s⁻¹) | Water depth (m) | Points |
|---------------------|-------------------|-----------------|--------|
| Weak                | 0–0.4             | 0–2             | HC1, HC2 |
| Medium              | 0.4–1.2           | 2–4             | HC3, HC4, HC5, HC6 |
| Strong              | >1.2              | >4              | HC7, HC8, HC9, HC10 |

Lithologic distribution of riverbed sediment

Riverbed sediment at different points showed stratification according to various characteristics, such as color and particle size (Figure 6). The lithology of the section could be described as mainly silty sand and fine sand, with silty soil and medium sand appearing at some points.

There were differences in the lithology of riverbed sediment among the different hydrodynamic zones, which was manifested as the thickness of the silt layer and average sediment particle size. The thickness of the silt layer was greater in the weak hydrodynamic zone compared with that in the medium hydrodynamic zone, while the silt layer in the strong hydrodynamic zone remained undeveloped. The rank of the zones according to the overall average particle size of sediment was: weak hydrodynamic zone < medium hydrodynamic zone < strong hydrodynamic zone. Therefore, there was a positive correlation between hydrodynamic condition and average particle size, which was consistent with the degree of riverbed scouring and clogging.
The lithologic profile of riverbed sediment (Figure 6) indicated that the thickness of the silt layer can act as an indirect indicator of the degree of siltation and can therefore serve as an indicator of the siltation category of riverbed sediment. Since sedimentation had a considerable influence on hydrodynamic conditions up to a sediment depth of 50 cm, the control section was divided into three zones of siltation degree: (1) strong; (2) medium; and (3) weak. Subsequent analyses will be discussed in terms of siltation zone.

The silt layer developed on the surface layer of the riverbed at the strong siltation zone (HC1 and HC2). After prolonged siltation, a relatively thick and stable fine particle layer was formed, with a surface silty soil thickness of 70 cm and an average particle size of 34.39 μm. The lithology of the sediment layer was mainly silty soil and silty sand. The average particle size in the medium siltation zone (HC3, HC4, HC5, HC6) was 103.75 μm, significantly larger than that of the sediment in the strong siltation zone. For example, the thickness of the silty soil layer at sampling point HC6 was 22 cm, which was not as thick as that at the strong siltation zone of 70 cm. Lithology below a depth of 22 cm was interbedded silty sand and fine sand. However, there was no silty soil layer on the surface of the weak siltation zone (HC7, HC8, HC9, HC10), and no particles with average particle size <16 μm were found, with the maximum average particle size being ~500 μm. Interbedding of silty sand and fine sand occurred on the surface layer of the riverbed at HC7, which was as a result of differences in river hydrodynamic conditions among different periods, resulting in differences in the degree of sediment deposition.

**Redox zoning in the hyporheic zone**

Riverbed surface lithology changes during siltation, resulting in changes to the permeability of the riverbed. These changes in the riverbed permeability result in clear variations in the water infiltration rate, residence time, and redox zoning in riverbed sediment. The present study focused on examining riverbed sediment within a depth range ≤50 cm, as this sediment zone is the most affected by lithology and siltation. Variations in indices that are sensitive to redox reactions (NO₃⁻, Mn²⁺, Fe²⁺, SO₄²⁻) were analyzed based on environmental indicators (DO, ORP, pH) and pore water chemistry data. The present study then compared redox reactions among the different sediment zones to reveal the effects of scouring and sedimentation on redox reactions.

**Environmental indices**

The DO of overlying water was 5.0–5.5 mg L⁻¹, whereas that of pore water was reduced to <1 mg L⁻¹ at a sediment depth of 5 mm. There were differences in the depths at which DO reached the detection limit among the different siltation conditions (Figure 7(a)), with the higher the degree of siltation, the shallower the depth at which DO reached the detection limit. Strong siltation resulted in an increased pore water travel time and a decrease in the depth at which DO decreased below the detection limit.

The ORP of overlying water was ~400 mV, indicating a relatively strong oxidation environment. The changes in ORP with depth were similar among different siltation zones (Figure 7(b)). Aerobic respiration occurred at a riverbed sediment depth ≤1 cm, and the decline in DO resulted in pore water moving from a relatively strong oxidizing environment to a weak oxidizing environment, with a rapid decrease in ORP. ORP fluctuated slightly within a depth range of 1–50 cm, whereas the redox environment remained basically stable.

The pH range of overlying water ranged between 7.5 and 8.5 with no obvious differences among the three siltation zones (Figure 7(c)). The pH of pore water remained basically stable between 7.0 and 8.0 with increasing sediment depth. There was a significant decrease in the pH of the surface layer of strong siltation zone. This observation can be explained by the longer residence time and sufficient biological respiration, which resulted in a greater production of CO₂ for release into the water and a consequent decrease in pH.

**Redox reaction sensitivity indices**

Monitoring of the redox sensitivity indices (O₂, NO₃⁻, Fe²⁺, Mn²⁺, SO₄²⁻, etc.) or the contents of reducing products (NH₄⁺, HS⁻, Fe²⁺, CH₄, etc.) in pore water (Appelo & Postma 2004) can be used to identify redox zones during surface water infiltration. As shown in Figure 8, the present study constructed curves showing the changes in redox
products at different depths below the riverbed as an approach to identify the redox zones, with the results showing that the index changed regularly with the infiltration distance (Figure 8).

The overlying water of the control section showed a high concentration of NO$_3^-$ which was unevenly distributed (Figure 8(a)). The spatial variation in NO$_3^-$ in the Liao River is due to the influence of fish and other aquatic organisms, and NO$_3^-$ accumulates in the surface layer of riverbed sediment. The concentration of NO$_3^-$ in pore water decreased significantly at a depth of $\leq 10$ cm, with the depth of the sediment zone in which the decrease occurred different among the different siltation zones. The depths of the zones in which NO$_3^-$ in pore water decreased significantly, which could be regarded as the positive reaction zones of nitrate reduction, were 5, 4, and 7.5 cm within the strong, medium, and weak siltation zones, respectively.

The concentration of Mn$^{2+}$ in the overlying water was generally low, ranging from 0.051 to 1.854 mg L$^{-1}$, with the highest concentrations found in the center of the riverbed (Figure 8(b)). The concentration of Mn$^{2+}$ peaked at a certain depth at points near the south bank (HC1, HC2, HC5), which could be attributed to the reduction of manganese oxide or hydroxide. However, Mn$^{2+}$ at points furthest from the south bank (HC6, HC7, HC10) remained basically unchanged with depth, with no reduction of Mn within 50 cm.

The concentration of Fe$^{2+}$ in the overlying water was low overall, with the highest Fe$^{2+}$ concentration at HC2 with a value of as much as 0.283 mg L$^{-1}$ (Figure 8(c)). The concentrations of Fe$^{2+}$ appeared the peak only at some points (HC1, HC2) at a depth of $\leq 50$ cm. There was no significant change in Fe$^{2+}$ content far from the south bank, with no clear reduction in Fe.

The concentrations of SO$_4^{2-}$ in the overlying water ranged from 20.347 to 56.435 mg L$^{-1}$, and were different among the different zones (Figure 8(d)). The degree of variation in SO$_4^{2-}$ with depth was greatly different among the

![Figure 7](image-url)
different points. SO\textsubscript{4}\textsuperscript{2-} concentrations showed clear increasing and decreasing trends at points close to the south bank (HC1, HC2). Therefore, sulfate reduction occurred at a depth \textlesss than 50 cm in the strong siltation zone, and sulfur oxidation also occurred at some points. SO\textsubscript{4}\textsuperscript{2-} concentrations generally remained stable in the lower concentration range at points far from the south bank (HC5, HC6, HC7, HC10), and SO\textsubscript{4}\textsuperscript{2-} reduction was relatively weak.

**Redox zoning in riverbed sediment**

Previous studies have been unable to identify a unified zoning standard and threshold for sequential redox zoning in the groundwater environment. The majority of past studies have determined the redox zonation threshold by the thermodynamic principle and the changes in concentration and the distribution characteristics of redox-sensitive indices in water (Lyngkilde et al. 1992).

Based on the analysis results of the environmental and hydrochemical indices of pore water, the present study determined that during the process of river water infiltration, oxidation-reduction occurs in the sediment-water interface under microbial action, with some ions participating as sequential electron acceptors. In addition, certain characteristics of redox zoning in the riverbed sediment were identified along the water flow path. The results showed that O\textsubscript{2} on the surface layer is the preferred electron acceptor during the initial stage of infiltration, and therefore, O\textsubscript{2} is the first electron acceptor to participate in the reaction. At the point at which oxygen is consumed up to a certain threshold, denitrification occurs, and there is a rapid decline in NO\textsubscript{3}\textsuperscript{-} concentration. Since there will generally be overlaps between O\textsubscript{2} and NO\textsubscript{3}\textsuperscript{-} in the reaction area, they will concurrently act as electron acceptors in an O\textsubscript{2}/NO\textsubscript{3}\textsuperscript{-} reduction zone. At a point at which the concentrations of O\textsubscript{2} and NO\textsubscript{3}\textsuperscript{-} reduce to a lower value, reactions involving manganese and iron oxides or hydroxides in the riverbed sediment initiate, resulting in higher concentrations of Mn\textsuperscript{2+} and Fe\textsuperscript{2+}, i.e., the Mn (IV) reduction zone and the Fe (III) reduction zone. Since the reducibility of manganese exceeds that of iron, the Mn (IV) reduction zone will appear first. As infiltration continues, SO\textsubscript{4}\textsuperscript{2-} will also participate in the redox reaction, forming an SO\textsubscript{4}\textsuperscript{2-} reduction zone.

The present study determined the thresholds of redox zoning (Table 3) according to the characteristics of environmental and hydrochemical indices combined with the degree of siltation. The redox zoning during infiltration was categorized according to the changes in DO, NO\textsubscript{3}\textsuperscript{-}, Fe\textsuperscript{2+}, Mn\textsuperscript{2+}, and SO\textsubscript{4}\textsuperscript{2-} concentrations with riverbed sediment sampling depth (Figure 8), and each zone was named according to the most important redox reaction in a particular zone (Figure 9).
Within the strong siltation zone, O$_2$/NO$_3^-$ reduction, Mn (IV) reduction, Fe (III) reduction, and SO$_2^4$ reduction were identified from the surface of the riverbed to a depth of 50 cm. Redox zoning was relatively dense, with some overlapping of zone points and a variety of simultaneous reduction reactions (Figure 9(a)). The strong siltation zone was characterized by fine lithology of the surface sediment, slow infiltration velocity, long residence time, and abundant organic matter, which provided enough electron donors to result in complex and abundant redox reactions.

Within the medium siltation zone, O$_2$/NO$_3^-$ reduction and Mn (IV) reduction occurred in the riverbed sediment up to a depth of 50 cm, and there was a trend of Fe (III) reduction. However, no SO$_2^4$ reduction zone was evident

### Table 3

| Redox zoning | DO | NO$_3^-$ | Mn$^{2+}$ | Fe$^{3+}$ | SO$_2^4$ | ORP | pH |
|--------------|----|----------|----------|----------|---------|-----|----|
| O$_2$/NO$_3^-$ | ≥LOD | Declining | Stable | Stable | Stable | Declining | Declining |
| Mn (IV)$^{2+}$ | <LOD | Stable | Peak | Stable | Stable | Stable | Stable |
| Fe (III)$^{2+}$ | <LOD | Stable | Stable | Peak | Stable | Stable | Stable |
| SO$_2^4$ | <LOD | Stable | Stable | Stable | Declining | Stable | Stable |

LOD, limit of detection; DO, dissolved oxygen; ORP, oxidation-reduction potential.

![Diagram showing the classification of redox zones for different siltation zones for a cross section of the Liao River, Shenyang, northeastern China](image-url)

**Figure 9** | Diagram showing the classification of redox zones for different siltation zones for a cross section of the Liao River, Shenyang, northeastern China: (a) strong siltation zone; (b) medium siltation zone; (c) weak siltation zone.
Compared with the strong siltation zone, the silt layer of the medium siltation zone was thinner, the water infiltration rate was faster and the travel time was shorter in the middle part of the siltation zone, resulting in a decrease in organic matter content, which limited the degree of strength of redox reactions.

Within the weak siltation zone, only the $\text{O}_2/\text{NO}_3^-$ reduction and Mn (IV) reduction zones appeared within the riverbed sediment depth up to 50 cm (Figure 9(c)). In contrast with the medium siltation zone, there was no complete Mn-reduction zone, indicating the presence of a large range of Mn (IV) reduction below 50 cm depth. Almost no silty soil was found on the surface layer, the overall lithology was coarse, water travel time was shorter, and there was a lower organic matter content, resulting in weaker redox reactions.

As shown in Table 4, the redox zonal ranges were identified by comparing and analyzing the redox sensitivity indices for different siltation zones. The degree of siltation was generally negatively correlated with the extension distance of the redox zoning in the riverbed sediment and positively correlated with the completeness of redox zoning. Due to the complex changes in hydrodynamic conditions, there were differences in mineral composition, and the action of microorganisms resulted in overlaps of the redox zones.

**CONCLUSION**

The present study analyzed the chemical composition and environmental indicators of pore water in riverbed sediment at different points along a cross-section of the Liao River, Shenyang, northeastern China. The observations of environmental and hydrochemical compositions of pore water were discussed in relation to differences in the degree of siltation. The riverbed sediment of the Liao River in the study area was divided into zones of strong, medium, and weak siltation under the influence of river hydrodynamics according to the different impacts on sediment permeability to water infiltration. Redox vertical zones within a riverbed depth of 50 cm were derived based on the three identified siltation zones from top to bottom into the zones of: (1) $\text{O}_2/\text{NO}_3^-$ reduction; (2) Mn (IV) reduction; (3) Fe (III) reduction; and (4) $\text{SO}_4^{2-}$ reduction. The strong siltation zone appeared to show overlapping redox zones, whereas Fe (III) reduction and $\text{SO}_4^{2-}$ reduction appeared not to occur at the medium and weak siltation zones. The differences in the degree of siltation resulted in variation in infiltration time and organic matter content in sediment, and consequently in variation in the extension distance of redox zoning. The lithology of sediment and redox zoning during bank filtration were clearly impacted by scouring and siltation. However, the influence of scouring and siltation on organic matter and microorganisms requires further study. RBF management should pay attention to variations in riverbed sediment and redox zoning to avoid pollution of groundwater by river water and to realize the full benefits of bank filtration.

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**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.
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