

# Monitored Natural Attenuation: A Remediation Strategy for Groundwater Impacted by Coal Combustion Product Leachate

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## ABSTRACT

Natural attenuation-based remedies rely on natural in-situ processes to break-down and/or sequester the contaminants of concern. Monitored natural attenuation (MNA) has been successfully employed at thousands of locations where organic compounds have impacted groundwater quality. MNA-Inorganic is an emerging remedy for metals, radionuclides, and other inorganic compounds. Implementation to date has been limited, but is increasingly gaining attention for its cost-saving potential. MNA-Inorganic is a potential remedial technology for coal combustion product (CCP) management sites that have impacted groundwater quality. While attenuation of organic contaminants is a well-understood remedy, attenuation of metals and radionuclides involves more complicated or interdependent sets of processes and has rarely been applied.

The publically available guidance documents on implementation of MNA-Inorganic are reviewed. State and federal regulatory programs providing for MNA-Inorganic remedies are summarized. Due to the limited knowledge base on its implementation, and a lack of uniformity in regulatory programs, determining the feasibility of MNA-Inorganic is currently highly site-specific. Innovative or unfamiliar site characterization strategies are often required to evaluate MNA-Inorganic strategies. Practical implementation requirements are discussed and evaluated for the common regulated inorganic CCP leachate constituents. The evaluation is conducted in the context of present management strategies and those proposed under the pending EPA rulemaking of 2010. In many cases monitored natural attenuation can be a viable remedial alternative for groundwater at CCP management sites.

## INTRODUCTION TO MONITORED NATURAL ATTENUATION FOR GROUNDWATER

Monitored natural attenuation is a strategy and a set of procedures used to demonstrate that physiochemical and/or biological processes in an aquifer will reduce concentrations of undesirable substances to levels below regulatory concern.<sup>1</sup> It has been broadly applied to releases of petroleum hydrocarbons in many hydrogeological environments. There has been less application of MNA to the remediation of inorganic or radiologic substances in groundwater than to organic compounds. While MNA of organic

contaminants is a readily accepted remedy at the State and Federal level, inorganic attenuation is more complicated and there is limited implementation experience in industry, science, and government.<sup>2</sup>

Metals, radionuclides, and/or other inorganic compounds are found in all aquifers. The mechanisms that regulate their release from solids and movement through aquifers are for the most part the same processes that control movement of inorganics in aquifers impacted by CCP Leachate. These processes *attenuate* the concentration of inorganics in groundwater by depositing inorganics on aquifer solids. Unlike organic compounds that break down from hydrolysis or bacterial action, a reduction in concentration of dissolved inorganic compounds requires water to be removed from the aquifer, or the compounds immobilized by conversion to, or adsorption onto, solids. When demonstrated that the mechanism and permanence of natural processes will result in attenuation of undesirable compounds to acceptable levels, then remediation can be conducted by verifying that the remediation proceeds as predicted. MNA relies on natural processes to remove contaminants of concern from groundwater resulting in lower cost, and less disturbance of ground and infrastructure.

Active or remediation of inorganic compounds in the subsurface may rely on processes that are similar to or the same as natural attenuation mechanisms. Active remediation often seeks to improve or hasten these natural processes through chemical or biological augmentation of the aquifer. There are not clear distinctions between the late phases of conventional groundwater remediation and MNA, but such distinctions may be unnecessary. Relying on limited or low-energy active remediation as a preliminary step, then achieving final remedial goals through MNA is sometimes called “enhanced MNA”, or “enhanced attenuation.” Active remediation methods for petroleum products often leave residual dissolved contamination that is degraded slowly, requiring monitoring under regulations allowing MNA. Enhanced MNA is a common strategy in hydrocarbon remediation and the principle is adaptable to inorganic MNA.

Few leachate or groundwater problems are likely to occur at CCP management facilities constructed after the mid-1990’s.<sup>3</sup> However, there are legacy CCP management sites where CCP leachate has impacted groundwater quality.<sup>3,4</sup> The author believes that environmental monitoring and response strategies for legacy CCP management sites will be more successful if the potential for MNA is given early consideration.

## AUTHORIZING STATUTES

There is heightened Federal regulatory focus on CCP management and new rules have been proposed by the US EPA.<sup>5</sup> Oversimplified, the rulemaking creates CCP disposal requirements more stringent than currently in force in most states. The rule will require groundwater monitoring at all CCP landfills or impoundments. The US EPA estimates that 467 coal-fired electric utility plants operating as of April 2010 are disposing of CCP and are potentially affected by the rule.<sup>6,7</sup> The same estimate indicates that 311 generation stations use landfills, or impoundments and landfills, and 158 plants rely only on impoundments for CCP management. CCPs are currently disposed of in 45 states

and the main producers of CCP are in the states of KY, TX, and IN.<sup>6,7,8</sup> There are other estimates available of the numbers of plants and disposal facilities but approximately 300 CCP landfills and 630 CCP surface impoundments exist in the United States.<sup>8</sup>

Any soil, groundwater or vadose zone clean-up activities required for CCP will also be regulated under RCRA.<sup>5</sup> MNA is a federally-recognized remedial technology that can meet RCRA Corrective Action requirements and could be included when remedial alternatives for legacy CCP management sites are evaluated. Implementation of MNA for inorganics at RCRA facilities is clearly and favorably proposed by the EPA in the 1999 *Office of Solid Waste and Emergency Response (OSWER) Directive 9200.4-7P*.<sup>1</sup> In that directive MNA is defined as:

“the reliance on natural attenuation processes (within the context of a carefully controlled and monitored site cleanup approach) to achieve site-specific remediation objectives within a time frame that is reasonable compared to that offered by other more active methods. The ‘natural attenuation processes’ that are at work in such a remediation approach include a variety of physical, chemical, or biological processes that, under favorable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil or groundwater. These in-situ processes include biodegradation; dispersion; dilution; sorption; volatilization; radioactive decay; and chemical or biological stabilization, transformation, or destruction of contaminants.”

Site characterization and assessment of MNA is different for organic and inorganic strategies. The focus in organic MNA is on a working understanding of the transformation rates and daughter products when organic chemicals break down in aquifers. Complex organic compounds are reduced to water, carbon dioxide, methane, and salts by biotic and abiotic processes in organic MNA. The science and engineering looks to the dissolved phase concentrations derived from groundwater samples. From those analytical results and aquifer dimensions and flow rates, the mass and flux of organic contaminants is evaluated over time. Meeting a single objective, mass reduction of organic compounds, is all that is needed to validate the organic MNA remedial approach.

For inorganic contaminants, the scientific and engineering investigations must consider both the dissolved and solid phase. This is because inorganic compounds are not destroyed (with the exception of some radioactive decay chains), but become comingled with the aquifer solids. Inorganic compounds that are removed from the dissolved phase are transferred to the aquifer solids in inorganic MNA strategies. The undesirable inorganic compound is not destroyed; its location is changed, from dissolved and mobile to immobile via incorporation into/onto a solid. Because inorganics are left in place, there is stakeholder concern about the stability and longevity of the remedial action. It is partly this uncertainty regarding inorganic MNA that drives the need for more in-depth study. While much of the chemistry is abiotic, biotic reactions

can be very important in some inorganic MNA pathways. Inorganic MNA has two focus points:

1. Demonstrate that the attenuation process is reducing contaminant mass in groundwater; and,
2. Demonstrate that the remediation will meet long-term stability criteria without intervention.

## PRINCIPLES OF INORGANIC ATTENUATION

The 1999 OSWER Directive <sup>1</sup> provides limited policy and implementation guidance for inorganic MNA. EPA indicates that: the site-specific mechanisms of attenuation of inorganic contaminants should be known; and, the stability of the remedial action should be evaluated under potential changes in conditions. The OSWER Directive is fairly specific about the classes of attenuation processes that may be proven effective, stating:

“MNA may, under certain conditions (e.g., through sorption or oxidation-reduction reactions), effectively reduce the dissolved concentrations and/or toxic forms of inorganic contaminants in groundwater and soil. Both metals and non-metals (including radionuclides) may be attenuated by sorption reactions such as precipitation, adsorption on the surfaces of soil minerals, absorption into the matrix of soil minerals, or partitioning into organic matter.”

“Oxidation-reduction (redox) reactions can transform the valence states of some inorganic contaminants to less soluble and thus less mobile forms (e.g., hexavalent uranium to tetravalent uranium) and/or to less toxic forms (e.g., hexavalent chromium to trivalent chromium). Sorption and redox reactions are the dominant mechanisms responsible for the reduction of mobility, toxicity, or bioavailability of inorganic contaminants.”

“It is necessary to know what specific mechanism (type of sorption or redox reaction) is responsible for the attenuation of inorganics so that the stability of the mechanism can be evaluated. For example, precipitation reactions and absorption into a soil’s solid structure (e.g., cesium into specific clay minerals) are generally stable, whereas surface adsorption (e.g., uranium on iron-oxide minerals) and organic partitioning (complexation reactions) are more reversible.”

“Complexation of metals or radionuclides with carrier (chelating) agents (e.g., trivalent chromium with EDTA) may increase their concentrations in water and thus enhance their mobility. Changes in a contaminant’s concentration, pH, redox potential, and chemical speciation may reduce a contaminant’s stability at a site and release it into the environment.

Determining the existence, and demonstrating the irreversibility, of these mechanisms is important to show that a MNA remedy is sufficiently protective.”

“Inorganic contaminants persist in the subsurface because, except for radioactive decay, they are not degraded by the other natural attenuation processes. Often, however, they may exist in forms that have low mobility, toxicity, or bioavailability such that they pose a relatively low level of risk. Therefore, natural attenuation of inorganic contaminants is most applicable to sites where immobilization or radioactive decay is demonstrated to be in effect and the process/mechanism is irreversible.”

There have been numerous advances in the understanding of the environmental geochemistry of inorganic compounds and metals since publication of the Directive in 1999. The inorganic MNA topics discussed in the Directive are still valid, and form a first step to evaluate inorganic MNA. Over the period of 2006-2010 EPA has released much more detailed guidance on implementation of inorganic MNA and the ITRC has published on practical and regulatory aspects of implementing MNA inorganic at the State regulatory level. These guidance documents are summarized in a following section.

## COAL COMBUSTION PRODUCT LEACHATE CHARACTERISTICS

Inorganic MNA relies on being able to observe, quantify, and in some cases modify subsurface chemistry. There are major differences in the chemical characteristics of leachate across the major groups of CCP (fly ash, bottom ash, pollution control residue), and complexities introduced by co-disposal of different CCPs.<sup>3, 8, 9, 10, 11, 12, 13</sup> The composition of leachate from CCP is highly variable. Controls on leachate chemistry are numerous AND are strongly influenced by site-specific factors. Leachate chemistry is influenced to variable and unequal degrees by:

- The type of coal;
- The basin, sub basin, mine, or seam it is produced from;
- Variability of coal composition within the seam;
- Coal cleaning and pretreatment processes;
- Combustion conditions;
- Pollution control operations;
- CCP handling;
- CCP management strategies – impoundments, landfills or combined methods; and,
- Climate and environmental factors - such as hydrology, geology, and weather.

The preceding list of factors, that ultimately control the success of inorganic MNA, is imperfect and not meant to be exhaustive. There is a large knowledge base on the geochemistry of CCP and CCP leachate.<sup>3, 9, 10, 11</sup> That information is very helpful to

constrain remedial strategies for legacy CCP sites, but does not replace the detailed site-specific assessment of ash and aquifer geochemistry required for inorganic MNA.

The United States Geological Survey (USGS) has been a major research participant in the investigation of the variability of coal chemistry and the resultant variability in CCP chemistry for many years. Coal composition has consequences for every aspect of coal-fired power production; from air quality through waste management. Similarly, coal composition has significant impacts on the composition of CCP leachate quality. During a recent conference USGS presented the finding of several research programs on coal and CCP composition and variability.<sup>13</sup> The primary finding with respect to implementation of MNA at legacy CCP management sites is that each site will have a different history of coal source, combustion, handling, management and disposal. So while there will be some similarities in CCP and leachate chemical composition a particular coal source with CCP managed in a similar manner, large differences in leachate composition and concentration are to be expected from site to site and over a generation stations operational history.

Compilations of CCP Leachate data are published by the US EPA as part of the ongoing Federal rulemaking on CCP disposal<sup>8, 9, 10, 11</sup> and EPRI (formerly the Electric Power Research Institute).<sup>3, 12</sup> EPA and EPRI used screening methods to identify COCs for further consideration. That data was used for the prevalence of various elements and compounds in CCP leachate and impacted groundwater. Occurrence data is used to draw inferences on the suitability of inorganic MNA as a remedial action at legacy CCP management sites. Two recent EPRI reports<sup>3, 12</sup> and three EPA characterizations<sup>9, 10, 11</sup> are used as primary sources for the expected leachate chemistry used here. The results of the comparison are presented in Table 1.

EPRI has conducted extensive research on the occurrence, concentration, and mobility of CCP leachate components. The selection criteria the used to identify constituents of concern (COCs) included prevalence, mobility, and risk as determined by comparison to water quality standards.<sup>3</sup> EPRI's assessment identifies five leachate constituents that are probably present in pore water at all legacy CCP management sites; arsenic, boron, chromium, selenium, and sulfate. Each of these substances has triggered at least one remedial action at a legacy CCP site. While these constituents are the primary focus of concern due to their prevalence and mobility, several other inorganic constituents may be of concern at legacy CCP management sites. From EPRI's 2006 effort the following constituents are noted:<sup>3</sup>

“The leachate data indicate that concentrations of antimony, arsenic, cadmium, chromium, selenium, and thallium were higher than health-based MCLs in at least 10 percent of the samples. In addition, the 90th percentile concentrations of boron, lithium, manganese, molybdenum, sodium, sulfate, and vanadium were higher than alternative drinking water criteria. These constituents are more likely to trigger a remedial action in the event of a leachate release than constituents that typically have leachate concentrations lower than drinking water standards.”

The EPRI listed constituents above are primary candidates for MNA because of their occurrence, mobility and propensity to exceed drinking water standards at legacy CCP sites. Not all of these constituents are amenable to remediation through MNA processes because of their chemical properties. Table 1 compares the leachate chemistry as identified by the previously listed EPA and EPRI sources, with the compounds suitable for inorganic MNA as found in the EPA, EPRI, and ITRC guidance documents.

The EPA sources cited <sup>9, 10, 11</sup> identify the following thirteen COCs based on the potential for human health and/or ecological impacts using a screening risk assessment: aluminum, arsenic, antimony, barium, boron, cadmium, cobalt, chromium, lead, mercury, molybdenum, selenium, and thallium. One of the findings of the 2009 EPA report was nine of the thirteen COCs listed above were found in CCP leachate at levels of concern for groundwater protection, as indicated in Table 1.

## PUBLISHED GUIDANCE ON INORGANIC MONITORED NATURAL ATTENUATION

### United States Environmental Protection Agency Guidance

The US EPA is the primary source of guidance on MNA. The EPA has published their inorganic MNA guidance in three volumes. Volume 1 is a procedural and technical guide for implementing MNA; <sup>14</sup> Volume 2 a detailed exploration of issues associated with inorganic MNA for nine compounds; <sup>15</sup> and Volume 3 contains discussion of MNA issues unique to radionuclides and a detailed exploration of inorganic MNA for ten radionuclides. <sup>16</sup> Volumes 1 and 2 were published in 2006 and Volume 3 in 2010. The EPA guidance documents cover inorganic MNA at a high level of scientific detail. The EPA guidance, while not specific to CCP, is a technical resource on evaluation of the feasibility of inorganic MNA for compounds as listed in Table 1.

Volume 1 introduces EPA's "Tiered Analysis Approach to Site Characterization"; the tiers being four demonstrations or findings to be accomplished when implementing inorganic MNA. Volume 1 provides specific technical guidance on implementing inorganic MNA using the four-tiered approach. Volume 2 expands on the technical guidance to include specific strategies and chemical mechanisms for arsenic, cadmium, chromium, copper, lead, nickel, nitrate, perchlorate, and selenium inorganic MNA. Volume 3 is presented the evaluation of MNA for radionuclides.

Table 2 presents a simplification of the four tiered approach found in the EPA guidance. CCP inorganic MNA is not considered by EPA to be a viable remedial alternative for groundwater unless the leachate additions to groundwater have been controlled. Developing a site-specific understanding of the mechanism by which inorganic MNA may attenuate (Tier II) and the capacity of the aquifer to do so (Tier III) is a complex and iterative task. Volume 1 provides the technical basis for inorganic MNA evaluations to accomplish Tier II and III goals. Monitoring of inorganic MNA is necessarily more detailed than for many active remediation strategies and is discussed in Volume 1.

Table 1. Compounds in CCP leachate as compared to MNA guidance.

	EPA CCP Leachate Data	EPRI CCP Leachate Data	EPA MNA	ITRC MNA	EPRI MNA
Aluminum (Al)	X	XX			
Antimony (Sb)	XX	XX			
Arsenic (As)	XXX	XXX	X	X	X
Barium (Ba)	XXX	X			
Beryllium (Be)	X	X			
Boron (B)	XX	XXX			X
Cadmium (Cd)	XX	XX	X	X	
Calcium (Ca)	X	X			
Chromium (Cr)	XXX	XXX	X	X	X
Cobalt (Co)	X	X		X	
Copper (Cu)		X	X	X	
Fluorine (F)	X	X			
Iron (Fe)	X	X			
Lithium (Li)		XX			
Lead (Pb)	X	X	X	X	
Magnesium (Mg)		X			
Manganese (Mn)	X	XX			
Mercury (Hg)	X	X			
Molybdenum (Mo)	XX	XX			
Nickel (Ni)	X	X	X	X	
Potassium	X	X			
Selenium (Se)	XXX	XXX			X
Silicon (Si)		X			
Silver (Ag)	X	X			
Sodium (Na)	X	X			
Strontium (Sr)		X		X	
Thallium (Th)	XX	XX			
Vanadium (V)	X	XX			
Zinc (Zn)	X	X		X	
pH	X	X			
Sulfate (SO <sub>4</sub> )	X	XXX			X
Dissolved Solids	X	XX			
Radionuclides			X	X	
	X=mentioned XX= of concern XXX=exceeds toxicity criteria	X= evaluated XX= of concern XXX=of concern and common			

Table 2. Summary of US EPA four tiered feasibility evaluation for inorganic MNA.

Tier I	Source Control	Is the contaminant mass in the plume decreasing?
Tier II	Attenuation Mechanism	Is the chemical mechanism well understood?
Tier III	Attenuation Capacity	Is the capacity and permanence of the mechanism sufficient?
Tier IV	Monitoring & Contingency	How will monitoring be conducted? What actions will be taken if monitoring indicates attenuation is lacking?

#### Interstate Technology Research Council Guidance

In late 2010 ITRC (Interstate Technology & Regulatory Council) published a decision framework for inorganic MNA. <sup>2</sup> The document contains a summary of the three-volume EPA guidance, expanded to decision framework for determining MNA feasibility. Case studies are included and compared to the EPA four tiered approach. <sup>14</sup> The MNA implementation at the state level was surveyed and reported. The ITRC document summarizes the topic of inorganic MNA, presents an introduction to the science, and presents a strategy for training and implementation of inorganic MNA under state laws and regulations. This guidance is not specific to CCP. As with the EPA guidance, it is a technical resource on evaluation of the feasibility of inorganic MNA for compounds as listed in Table 1.

Twenty-four states responded to the ITRC survey <sup>2</sup> (AR, AZ, CO, CT, FL, GA, IL, IN, MD, MO, NJ, NY, OH, OK, OR, PA, SC, TN, UT, VA, VT, WA, WI, WY). The results were generally favorable for implementation of inorganic MNA in those states. MNA has been used for inorganics in 17 of the 24 states surveyed. Four of the states surveyed do not statutorily cite inorganic MNA as a remedial action (Arkansas, Illinois, Maryland, and Oregon), but with exception of Illinois, allow MNA on a case-by-case exception to the restriction. Illinois will not allow MNA of metals or radionuclides. Illinois and Maryland do not allow MNA as a remedial option for organic constituents either. All states reported that they use Federal Maximum Contaminant Levels for groundwater cleanups, with Oregon and Wisconsin being more stringent for some constituents.

#### EPRI Guidance

There is substantial literature on the environmental properties of the compounds found in CCP leachate. In addition to the academic literature industry-supported organizations such as the American Coal Ash Association and EPRI have conducted investigations for many years into the chemistry and environmental properties of CCP and CCP leachate. EPRI published a CCP leachate specific report in 2006 considering the application of permeable reactive barriers to groundwater remediation. <sup>3</sup> The EPRI report provides guidance on many in-situ and ex-situ technologies for groundwater remediation at CCP management sites. The EPRI reactive barrier report contains a section on MNA as a remedial alternative and other sections on in-situ technologies that have common

chemistry with some MNA processes. As with the EPA reports, there is a high level of technical detail found in the EPRI document. The EPRI report was published before the EPA guidance was available for review and the authors were aware of the EPA guidance in preparation. The EPRI guidance is not structured in the same manner as provided by EPA, but relies on the same science and general criteria for evaluation to accomplish inorganic MNA. The EPRI compound-specific MNA evaluations were limited to arsenic, boron, chromium, selenium, and sulfate; the remaining COC's after EPRI screening criteria was applied.

#### SUMMARY: MNA IMPLEMENTATION FOR MAJOR CONSTITUENTS IN CCP LEACHATE

The four tiered approach of the EPA, the vast EPRI and academic research, and ITRC decision framework provide sufficient guidance on how to execute inorganic MNA evaluations for legacy CCP sites. As discussed in the preceding sections, and in much greater detail in the guidance documents, inorganic MNA requires a comprehensive site-specific investigation of aquifer parameters. Many of these tests are not conducted during active remediation feasibility studies or design. Models are essential components of the MNA or in-situ treatment evaluation process and must reflect often complex site conditions. Evaluation of the potential for inorganic MNA is not trivial from a cost or effort standpoint. Investigation of MNA feasibility will be phased and iterative, and monitoring periods can be lengthy. Even with these constraints and requirements, inclusion of inorganic MNA in the overall remedial strategy can achieve objectives at lower cost than without MNA. Costs for active remediation of inorganic compounds in groundwater can also be very expensive, and may eventually involve inorganic MNA from a technical necessity.

The proposed rule regarding CCP management <sup>5</sup>, if implemented, could mean that Federal guidance regarding inorganic MNA could be applied to all states. This would increase remedial alternatives that could be used at legacy CCP sites, albeit at an extreme cost to the industry. Currently, regulation of the use of inorganic MNA will be determined on a state by state basis and some states with CCP disposal do not allow inorganic MNA as a remedial alternative.

If proposed rule requirements for impoundment closure are implemented it is near certain that there will be dewatering and other active site groundwater management activities. It is furthermore near certain that closure will alter existing subsurface geochemical conditions. This presents hydrologic and geochemical opportunities to significantly alter subsurface conditions, enhancing attenuation of CCP leachate impacted groundwater. Similarly, unintended changes to aquifer biogeochemistry could exacerbate preexisting contaminant conditions, making remediation less tractable and more expensive than necessary. A holistic approach to site groundwater biogeochemistry under the current laws allowing MNA, or under any of the currently proposed regulatory options, offers the potential for cost savings through inorganic MNA implementation or by avoiding unintended consequences.

The EPRI COC list for the compounds of most concern in CCP leachate impacted groundwater (arsenic, boron, chromium, selenium, and sulfate) is used here to examine some of the MNA-related controlling factors for these constituents. I have developed Table 3 to present a matrix of probable chemical pathways for MNA of the EPRI COCs. Many of these pathways are applicable to the range of leachate components presented in Table 1. Numerous other potential pathways exist for components in Table 1 that are not reflected in Table 3. With exception of boron, MNA pathways exist for the EPRI CCP leachate COCs. Some MNA biogeochemical pathways are incompatible with each other; site-specific conditions are the primary consideration in evaluating MNA potential at legacy CCP sites. Here we have summarized and presented an overview the current potential for inorganic MNA of these components.

Table 3. Potential MNA pathways for five EPRI CCP leachate constituents of concern.

	Arsenic	Boron	Chromium	Selenium	Sulfate
Sorption	Attenuated by sorption and oxidative co-precipitation with iron and manganese. Stabilized as a sulfide.	Not well attenuated by sorption on geomeia.	Stabilization by reduction of Cr(IV) to Cr(III) and precipitation. Some adsorption of Cr(IV) to iron oxyhydroxides. Coprecipitated with sulfides.	Some adsorption to iron oxyhydroxides.	Not well attenuated by sorption on geomeia.
Dispersion and Dilution	Concentration reduction by mixing.	Concentration reduction by mixing.	Concentration reduction by mixing.	Concentration reduction by mixing.	Concentration reduction by mixing.
Biogeochemical	Attenuated in biogeochemical reactions that precipitate iron oxyhydroxides.	Limited uptake by biota. Does not participate in microbial respiration/fixation processes.	Attenuated in biogeochemical reactions that precipitate iron oxyhydroxides.	Microbial processes cause reduction to Se(0) and fixation as Se(0) or FeSe. Sequestration in wetlands sediments.	Sulfate reducing bacteria cause reduction of sulfate to sulfide compounds and precipitation of metal sulfides

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