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Decision-making framework for the application of *in-situ* activated carbon amendment to sediment

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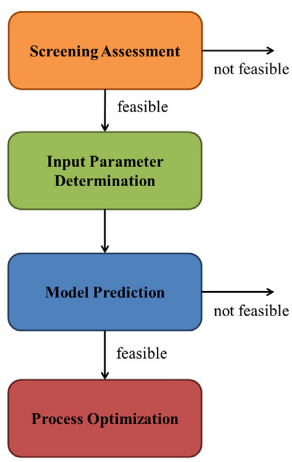
HIGHLIGHTS

- Decision-making framework is developed for *in-situ* AC amendment to sediment.
- A guidance is provided for each step of the decision-making framework.
- The state-of-the-art assessment methods for the treatment technique are applied.
- The modeling approach supports long-term prediction and engineering design.

GRAPHICAL ABSTRACT



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ABSTRACT

This study provides a decision-support framework and a design methodology for preliminary evaluation of field application of *in-situ* activated carbon (AC) amendment to sediment to control the (bio)availability of hydrophobic organic contaminants. The decision-making framework comprises four sequential steps: screening assessment, input parameter determination, model prediction, and evaluation for process optimization. The framework allows the application of state-of-the-art experimental and modeling techniques to assess the effectiveness of the treatment under different field conditions and is designed for application as a part of a feasibility study. Through a stepwise process it is possible to assess the effectiveness of *in-situ* AC amendment with a proper consideration of different site conditions and application scenarios possible in the field. The methodology incorporates the effect of various parameters on performance including: site-specific kinetic coefficients, varied AC dose and particle size, sediment and AC sorption parameters, and pore-water velocity. The modeling framework allows comparison of design alternatives for treatment optimization and estimation of long-term effectiveness over a period of 10–20 years under slow mass transfer in the field.

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1. Introduction

In-situ activated carbon (AC) amendment is a new technology for the treatment of hydrophobic organic contaminants (HOCs) in sediments. The technique is expected to grow in acceptance as a treatment option because there is a strong need for an in-place, cost-effective, and non-destructive sediment management approach as an alternative or adjunct to dredging or capping [1]. Since the first laboratory demonstration by Zimmerman et al. [2], researchers in the U.S. and Europe have successfully proven the effectiveness of the technology to reduce HOC equilibrium aqueous concentration, uptake by benthic invertebrates, and flux into the water column for various groups of compounds including polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and organochlorine pesticides [3–12]. Successful pilot-scale studies have been conducted at several sites in the U.S. and Norway with varied site conditions and modes of application [13–18].

While the laboratory studies and field trials are encouraging, they also revealed that the effectiveness of the treatment is somewhat variable from site to site depending on the properties of the target contaminant, site conditions, and engineering options applied for the treatment [13–16,18]. Also of concern is the long-term effectiveness of the amendment, as to date the field performance of AC in pilot studies has been monitored for no more than five years [16]. Rather than removing contaminants from the site, the AC treatment targets the reduction of the (bio) availability of the contaminants that exist in sediment. Therefore, it is important to verify that the contaminants sequestered by AC will not be released back to the sediment or pore-water and become available to aquatic organisms in the long term. Monitoring results to date suggest that AC performance continues to improve with time in accord with mass transfer models (Cho et al. [16], Choi et al. [4])

In the field, AC can be delivered to the sediment in either of two modes: mechanical mixing of AC into sediment or applying AC as a thin-layer. For mechanical mixing, a device is employed to mix the AC into the biologically active layer of sediment (*e.g.*, 15–30 cm) to reduce the bioavailability of HOCs in sediment to benthic organisms and to diminish the likelihood of AC being transported off-site by waves or currents [14,18]. For thin-layer AC application, AC is spread onto the contaminated sediment with the expectation that the bioturbation action by benthic organisms will eventually mix AC into the sediment [15]. The expected benefit of thin-layer AC application is the reduction of HOC flux to the water column in the short term and the reduction of HOC bioavailability to benthic organisms in the long term after significant bioturbation activity.

This study focuses on an assessment framework for mechanical mixing of AC with sediment as a delivery method because of the current knowledge and accumulated experience for this method of deployment compared to a thin-layer AC application. This knowledge provides a more robust database for the modeling and experimental approaches employed in the assessment framework. The framework may also be applicable to thin-layer applications if significant AC mixing occurs by bioturbation after thin-layer capping of AC and if the AC distribution pattern and mixing depth resulting from the bioturbation can be characterized.

To date, various studies have been conducted to improve the mechanistic understanding of *in-situ* AC amendment and to evaluate the effectiveness of the treatment for different situations. Laboratory studies [2–4,6,8,19–21] characterized the effects of compound properties, site-specific properties, and various engineering options on the effectiveness of AC amendment. Building on these laboratory observations and theoretical analyses, an HOC mass transfer model was developed to predict the effectiveness of *in-situ* AC amendment [9,16,22,23]. This model was shown to provide reasonable estimate of treatment effectiveness for a pilot-scale study on PCB-impacted sediments [16]. Using results from 24-month column studies in the laboratory, the model adequately described the effects of contaminant properties, site sediment properties, and AC dose and particle size [23].

Hence given the experience in the last decade, it is timely to incorporate the state-of-the-art modeling and experimental tools in a framework that enables an engineering assessment of the short- and long-term effectiveness of the treatment technique in the field. This aids decisions as to whether *in-situ* AC amendment is a valid treatment option that offers an efficient and cost-effective treatment of HOCs in sediments when site conditions are favorable for its application.

In this paper, a decision-making framework for the assessment of *in-situ* AC amendment is presented to apply the current level of scientific knowledge to evaluate the feasibility of the treatment. The content of the framework includes preparation, execution, and utilization of the HOC mass transfer model to quantitatively predict the short- and long-term effectiveness of the treatment under different site conditions and practical engineering options. The framework is designed for use during a feasibility study to enable consideration of *in-situ* AC amendment in comparison with other treatment options.

2. Requirements for the assessment framework

The framework for the site-specific assessment of *in-situ* AC amendment assumes that the site has been adequately characterized to determine remedial objectives. To support the assessment framework proposed here, the site characterization should address the questions shown in Table 1 and the answers to the questions should correspond to the conditions described therein.

The primary risk-driving sediment contaminants should be hydrophobic organic compounds (log $K_{ow} > 3$). The experimental and modeling procedures for the framework have been developed using HOCs such as PAHs, PCBs, and DDT (dichlorodiphenyltrichloroethane) as target contaminants. For relatively less hydrophobic compounds, the validity of the assessment results obtained following the framework would need to be evaluated with additional testing.

The objective of *in-situ* AC amendment is to reduce (bio) availability of contaminants in sediment, which results in reduced contaminant risk to aquatic biota and humans. As contaminants are not chemically transformed or physically removed from the sediment, there is no change in the bulk sediment concentration following AC deployment. Therefore, a measure of the treatment effectiveness should not be based on absolute contaminant concentration in sediment. For the proposed assessment, it is most convenient to use the sediment pore-water concentration as an indicator of AC performance. Sediment pore-water concentrations have been used most frequently to quantify the effectiveness of AC treatment in pilot studies, laboratory experiments, and numerical modeling [2,4,14,16,18,22,23]. HOC accumulation in representative benthic organisms is an appropriate indicator as well, and is a direct measure of HOC bioavailability. Finally, the success of treatment can be defined on the basis of the modeled "effective" sediment HOC concentration (*i.e.*, sediment HOC concentration in the sediment-phase only, excluding HOCs sorbed to AC). HOCs sorbed to AC exhibit substantially less bioavailability than those associated with sediment [10,24]. Therefore, the modeled reduction in the effective sediment concentration indicates the reduction in contaminant bioavailability and thus, the effectiveness of the AC amendment. The limitation of using effective sediment concentration as an indicator is that the actual values cannot be directly measured in the field.

For the assessment framework proposed in this study, it is important that the site be characterized and a numerical cleanup