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Capping as *in-situ* alternative for contaminated sediments

Agnieszka Popenda

Department of Environmental Engineering, Faculty of Infrastructure and Environment, Czestochowa University of Technology, Dabrowskiego St. 69, 42-200 Czestochowa, Poland, Tel. +48 343250909; email: apopenda@is.pcz.czest.pl

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ABSTRACT

The paper presents the possibility of using sediment capping as an *in-situ* method of treatment contaminated sediments. The amendments applied in sediment capping were also included as well as the capping equipment and application methods. Factors influencing capping which include: characteristics of sediments, hydrology and geology, erosion, the thickness of the layer, infrastructure and waterways, changes in the environment, monitoring were described in the paper. The following aspects of capping modeling were pointed out: sorption, diffusion, the behavior of the aquatic sediment matrix, the fate and transport of contaminants during landfill containment and after remediation. The examples of implementation of the discussed method in practice were also given. In several cases, recontamination of the seabed after capping occurred due to the point sources as well as runoff from landfills from the land and/or from impervious surfaces via surface water. The paper also concerns the advantages and limitations of capping applications. The following advantages of capping should be mentioned: reduction of exposure of aquatic environment to contaminants in a short time, less infrastructure of material handling, therefore is less expensive than *ex-situ* methods, effectiveness technique in the aspect of long-term containment of contaminants. The main limitations of capping are: contaminated material is not removed from the aquatic environment, monitoring is required at capping sites during and after construction, the usage of cap materials may alter the biological community, strong currents can displace capping materials, the equipment for placement of dredged material *in-situ* capping projects is suitable mainly in harbors or rivers. In order to avoid a cap from disturbances, the application of the waterway may be limited if a river with contaminated sediment deposits is shallow. In further activities, the attention should be paid into fate processes in caps as well as complex biological, chemical and physical processes affecting the caps and individual contaminants.

Keywords: Pollution; Sediments; Capping of sediments; *In-situ* treatment; Amendments; Modeling

1. Introduction

A significant amount of pollutants introduced into the aquatic environment as a result of human activity accumulates in sediments [1]. These are mainly inorganics (heavy metals) which are characterized by low solubility and difficulty of degradation, as well as organic compounds such as polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCBs), organochlorine pesticides, phthalate, esters and cyanides [2,3]. The accumulation of harmful and persistent organic pollutants in sediments as well as in aquatic food chains is a major environmental concern [4]. Pollutants accumulated in sediments may be a secondary source of water pollution if conditions favorable for such processes as a decrease of pH, change of oxidation–reduction conditions, an increase of salinity, concentrations of heavy metal complexing compounds appear [5–7]. However, even under stable physicochemical conditions of the aquatic environment, pollutants can also migrate from the sediment to water, especially when they are bound to

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the sediment in a non-persistent way, for example through adsorption bonding. Then, even the movement of sediments caused by water waves can result in the release of the water. Additionally, unfavorable natural conditions such as flood or anthropogenic, that is, dredging, construction of water structures, water transport result in the secondary contamination of water by sediments [7,8].

The problem of sediment pollution concerns most natural reservoirs, dam reservoirs, canals as well as floodplains and backwaters, as well as rivers flowing through urbanized and industrialized areas. They contain concentrations of persistent pollutants many times higher than in waters. The impact of accumulated pollutants in sediments on water quality often prevents or limits the economic and environmental use of significant water resources [9]. In order to eliminate or at least reduce the adverse impact of sediments on water quality methods and techniques for their removal from water bodies, their isolation from the water phase and remediation were developed, both at their place of origin (*in-situ*) and after dredging (*ex-situ*) [10,11]. The choice of treatment method depends on many factors and above all on the level and type of contaminants in the sediment. The disadvantages of *ex-situ* methods, such as high costs of dredging, transport and storage of sediment, possible re-suspension of sediment and release of pollutants into the water resulted in the searching for the alternative methods of neutralizing contaminants in sediments, that is, disposal of contaminated sediments in the aqueous environment without excavating, that is, *in-situ* conditions [12,13]. Among the remediation methods of lakes, water reservoirs, anthropogenic floodplains and rivers, underwater capping of contaminated sediments is considered a promising and low-cost method of remediation in the last decades. Therefore, the brief overview of the capping including materials apply for covering layer, equipment and application methods, factors influencing capping, modeling of capping, examples of implementation of capping in practice and advantages and limitations of the method is presented in the article.

2. Capping as in-situ method

Nowadays two *in-situ* capping strategies have been distinguished: conventional and active [14,15]. Covering sediments (capping) consists of placing an underwater cover or layer of clean material and/or synthetic materials on contaminated sediments to fully only isolate (not reduce) pollutants from the surrounding aquatic environment [16]. In conventional capping technology, chemical reactions such as adsorption, precipitation, oxidation/reduction are not required. The conventional cover layer is generally made of granular material such as clean material sediments, sand, clays or gravel to prevent contaminant resuspension and migration [17–20]. The aforementioned materials are commonly available, relatively cheap and easy to place [18]. The covering layer made of natural sand is generally considered to be better than that dredged from other areas because the naturally occurring fine fraction and the organic carbon content are more effective in chemical isolation due to their ability of binding contaminants. However, sand containing a large fine material fraction may also increase the turbidity during the layer application process. Under certain circumstances sometimes more complex layers may be required to meet site-specific requirements [18]. The scheme of conventional capping systems design is shown in Fig. 1 [19,20].

In thin-layer capping (so-called enhanced natural recovery) capping material is applied but at lesser thicknesses depending upon the variation in ground surface or water levels at the site [21].

Modifications of the *in-situ* capping method involve the usage of a covering layer after partial removal of contaminated deposits or the installation of innovative layers containing active ingredients [21]. Active capping technology includes special amendments that promote the chemical degradation (binding and precipitation in the case of inorganics) or support chemical and biological degradation and the reduction of toxicity in pore waters and surface sediments (in the case of organics) [22].

The function of cap amendments is to retard the migration of contaminants encourage degradation within the cap or to provide finite sequestration capacity. The group of active covering materials characterized by increased sorption capacity and the ability to physicochemical changes of heavy metals can be distinguished [23]. The recent studies proved that sorptive amendments such as activated carbon, organoclay, apatite, biochar, coke, zeolites, and zero-valent iron are regarded to be very effective in sediment treatment [24–29]. Activated carbon is produced from coal or biomass feedstock, and treated at high temperature to produce a highly porous structure with great sorption capacity. Activated carbon has been used both in laboratory experiments and field-scale applications to control dissolved hydrophobic organic compounds [25–27]. Apatite is effectively applied to sequester metal contaminants, whereas zero-valent iron encourages the dechlorination of chlorinated benzenes and PCBs [27–32].

Modern approaches incorporate more complex cover materials such as geotextiles, primers or other permeable or impermeable materials in multilayer systems that may contain additives to reduce contamination (e.g. organic carbon) [15]. Porous geo-textiles do not contribute to the isolation of the toxic agent but reduce the risk of mixing and movement of the underlying sediments with the cover layer material [28]. In some cases, several layers of different materials are used, whereas in other cases a single layer fulfills the requirements.

Examples of effective use of additives for sediment at a pilot-scale level are as follows AquaBlok® (Swanton, U.S.) – patented technology or bentonite based on a mineral covering clay capped with the layer of clay mixed with polymers that expand in water to control permeability, AquaGate+PAC (a powder-activated carbon delivery system that uses the AquaBlok®, Swanton, U.S.) and Sedimite™ (Elicot, U.S.).

A similar technology, reactive core mats (CETCO®, Hamilton, U.S.), involves the placement apatite, activated carbon, organoclay between geotextile fabrics, which are then applied atop the sediment. Other cap materials include BioSoil™ (Haghorst, Nl) (high organic content from composting to encourage degradation of organic contaminants), OrganoClay sorbents, Ambersorb sorbent (Philadelphia, U.S.), and coal-based sorbents [33].

Reactive materials (i.e., amendments) can be applied to sediments containing halogenated or nonhalogenated volatile

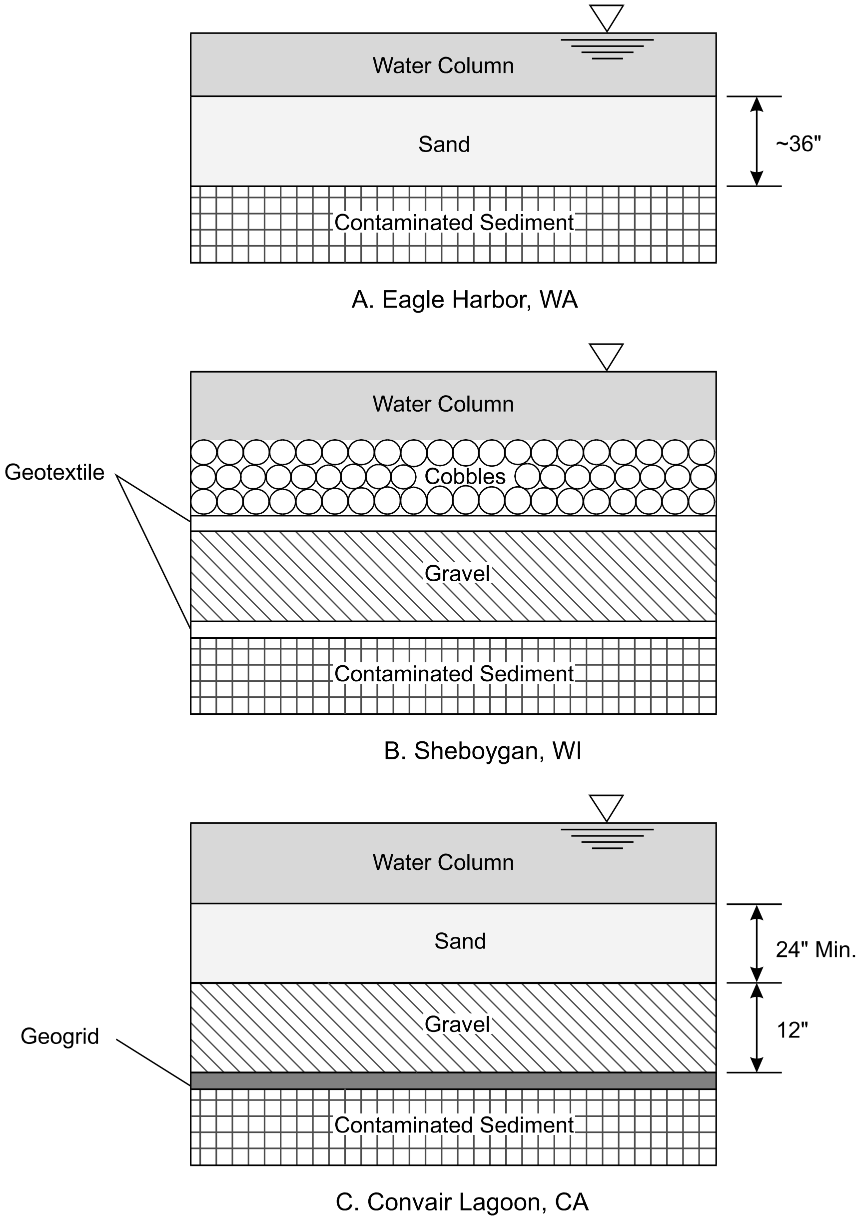

Fig. 1. Capping systems design [19,20].

organic compounds and semi-volatile organic compounds, PCBs, PAHs, ordnance compounds (e.g., trinitrotoluene and nitramines (3,5-trinitro-1,3,5-triazinane)), and metals/metalloids (e.g. arsenic, chromium, lead, mercury, etc.). Reactive mats have applications for PCB/PAH contaminated sediments [3,16,29]. The materials apply in capping according to the contaminants to be removed are given in Table 1.

3. Capping equipment and application methods

An important issue in choosing to cap is the need for controlled, accurate application of the layer materials [34]. A slow, uniform application that will affect the laying of the material in the layers is often necessary to avoid displacement or mixing with the underlying contaminated sediment. The granular material for the cover layer can be transported and applied in several ways. Mechanically extracted materials and soils from land-based locations and quarries usually contain relatively little free water. Such materials can be manipulated mechanically in the dry state until they are thrown into the water at the place of contamination. Hydraulic codes are precise, although the energy required to transfer the suspension may need to be dispersed to prevent secondary sediment suspension [33]. The material for the layer of reinforcement (e.g. stone breakage) can be dropped from barges or shore using conventional equipment such as chargers. Placing some components of the cover layer, such as geotextiles may require special equipment [34]. The covering material will have to be placed quickly, mainly if currents, waves, or tidal conditions rapidly

Table 1
Materials apply in capping according to the contaminants to be removed [24–33]

Capping material	Contaminant(s)/role
Granular clean sediment, clay, sand, gravel	Physical isolation of contaminants organic, inorganic and metal contamination including halogenated or non-halogenated volatile organic compounds and semi-volatile organic compounds, polychlorinated biphenyls (PCBs), ordnance compounds, nutrients, heavy metals, and radionuclides
Activated carbon	Sequestration agent PAHs, PCBs, dioxins, furans, Hg, various metals
Clay aggregate composite materials	Permeability control
Organoclays	Adsorption of insoluble and partially insoluble compounds and non-aqueous phase liquid control
Phosphate additives (apatite)	Metal contaminants, sequestration of lead, coke, coke breeze, and fly ash
Zero valent iron	Chlorinated benzenes and PCBs
Biopolymers	Binder for metals and organics which can be introduced by injection into the sediments

change. An example of capping equipment and application techniques is given in Fig. 2. The advantages and limitations of capping application techniques are included in Table 2.

4. Factors influencing capping

Depending on the type of pollutant and sediment, the main role of the covering layer is to reduce the risk of contamination release taking into account [15,16]:

- Isolation of the contaminated sediment, sufficient to reduce the exposure resulting from direct contact and reduce the possibility of contamination entering the surface as a result of the activity of the organisms,
- Stabilization of contaminated sediment and protection against erosion of sediment and a cover layer, sufficient to reduce re-suspension (secondary presence of pollutants in the suspended form, that is, to water) and transport to other places.
- Among technical factors to be considered in capping the following are of high importance: the contaminants properties characteristics of sediments, hydrology and geology, erosion, the thickness of the layer, changes in the surrounding environment, infrastructure and waterways, as well as monitoring [19].

4.1. Characteristics of sediments

In order to assess the susceptibility of the sediments to contaminant migration particle-size distribution unsaturated hydraulic conductivity, permeability and permeance (vapor movement potential) should be considered. If contaminants may degrade under aerobic/oxidizing, anaerobic/reducing, acidic or alkaline conditions the assessment of the oxygen content, carbon dioxide content, pE/Eh values, pH values, or other indicators, may be helpful to estimate if conditions will promote the natural degradation of contaminants [1]. The organic content of the sediment may be related to the mobility of non-ionized organic compounds, and the pH can give information on the mobility of inorganic and some ionized organic contaminants [7].

Capping can influence the change of conditions in the top layer of sediments from oxidizing to reduction, which results in the solubility of toxic compounds containing metals and the susceptibility of organic contaminants to decomposition by microorganisms. For example, many divalent metal cations (Pb, Ni, Zu) may become less soluble under anaerobic conditions, unlike other metalloid ions (e.g. arsenic) that become more soluble [6]. Mercury in the presence of sulfates, in an aqueous porous medium, can be methylated by anaerobic bacteria, and chlorine-substituted PCBs can be degraded to less chlorinated forms under anaerobic conditions [13]. When contaminated deposits are covered, the chemical conditions in the contaminated zone change. Mercury is generally limited as is the decomposition of organic matter and biological processes. The organic matter remaining under the cover layer can be degraded by anaerobic microorganisms and methane and gases are released with hydrogen sulfide. When these gases accumulate, they can pass through the layer by diffusion or convection. This process may cause some of the contaminants to dissolve and migrate upward in the gas bladders. The grain size of the layer material determines in part how the route of this transport will go. The cover layer of fine material may after a certain time contain gaps filled with gas, while a coarse material, such as sand, will allow gases to enter. However, in some cases, the insulating capacity of the cover layer causes the underlying layers to remain cooler and therefore the rate of decomposition decreases. When the amount of gas produced can be significant, this factor should be taken into account when designing the cover layer [11].

4.2. Hydrology and geology

In designing of the cap the following aspects of hydrology and geology should be taken into considerations: depth to water, range of seasonal groundwater fluctuation, the size of the water reservoir, depth and inclination (bathymetry) of the trough with sediment, water flow characteristics including tides and outflows, water current and other potential factors such as ice erosion and natural or man-made features that may control transient flows [13].

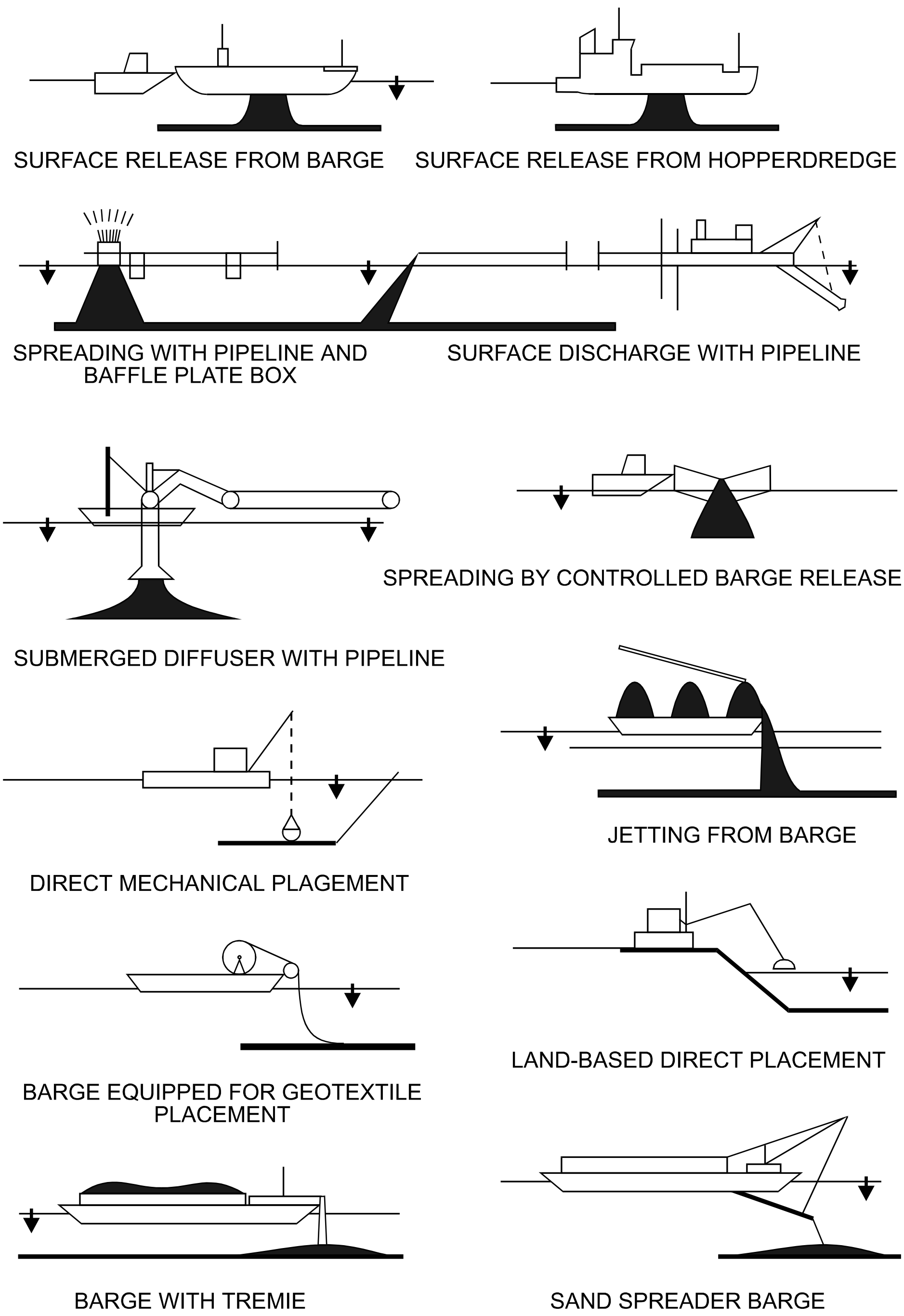

Fig. 2. Capping equipment and application techniques [34].

4.3. Significance of erosion

The strength of erosion depends mainly on the intensification of lateral forces in the river or basin coming from the river current, tides, waves or turbulence caused by ships and boats passing due to the impact of propellers and the shifting hulls themselves, as well as the properties of sediments such as grain size, their mineral type and density of their mass in the bed. In some locations, there is also a risk of seismic damage, especially where the contaminated deposits and the covering layer material have a low resistance to destructive forces [11]. In the open water zone, deeper places are generally less influenced by wind or current caused by waves and less susceptible to erosion than shallow coastal environments. However, reinforcements (bottoms, banks) and the choice of erosion-resistant material for cover may allow it to be used in some high energy environments. The currents in the water column can affect the dispersion during the application, as

Table 2
Advantages and limitations of capping application techniques [19,33]

Lp	Application technique	Advantages	Disadvantages/limitations
1.	Direct mechanical placement	Can be used for the nearshore areas to be capped	Reach of the equipment
2.	Surface discharge using conventional dredging equipment	Can be considered for placement of both contaminated and capping material	Not be applicable for soft fine-grained contaminated sediments
3.	Spreading by barge movement	Successfully used for controlled placement of predominantly coarse-grained, sandy capping materials	Not suitable for spreading cap materials in shallow water
		Cap layers can be spread over large areas by gradually opening a split-hull barge	
4.	Hydraulic washing of coarse sand	Technique produces a gradual buildup of cap material	
		Prevents any sudden discharge of a large volume of sand	
		Suitable for water depths as shallow as 10 ft. or less	
5.	Spreading by hopper dredges	Can be used to spread a sand cap with greater uniformity	
6.	Pipeline with baffle plate or sand box	Commonly used in river dredging operations where the material is deposited in thin layers in areas adjacent to the dredged channel	
		Well-suited to the placement of thin layers over large surface areas	
7.	Submerged diffuser	Can provide additional control for submerged pipeline discharge	Requires control when capping newly placed slurry with a diffuser and the need for adequate time to allow for some self-weight consolidation of slurry material prior to capping
		Confined the discharged material to the lower portion of the water column	
		Reduced suspended solids in the upper portion of the water column	
		Effective in reducing sediment resuspension and in controlling the placement of contaminated sediment	
8.	Sand spreader barge	Employs the basic features of a hydraulic dredge with submerged discharge	
9.	Gravity-fed Downpipe (Tremie)	Can be applied for submerged discharge of either mechanically or hydraulically handled granular cap material	

well as the selection of equipment used for covering. Bottom currents can cause destructive forces (parallel to the bottom) affecting the surface of the cover layer, which can potentially lead to erosion. Apart from natural river currents, the influence of storm waves and other phenomena (e.g. floods) should be taken into account [11].

4.4. Thickness of the layer

The covering layer should be thick enough to effectively separate contaminated sediments from aquatic organisms living or feeding on, above or in the cover layer. Typical conventional caps thickness applied in capping may be highly variable, from the order of 10 cm to minimum cap thicknesses of 50–60 cm [20,21]. The appropriate layer thickness should reduce the exposure of aquatic organisms to toxic compounds and reduce the ability of the feeding organisms (e.g. some species of mud shrimps) to move with a layer of the pollutants to the surface [14]. Thus, the thickness of the zone of effective mixing as a result of the bioturbation of the population of organisms in the sedimentation profile should be considered. Especially in the marine environment, the probability of colonization of the cover layer by deep-infesting organisms may decide to increase its thickness. Precautions to prevent colonization or damage to the cover layer by reaping bottoms may be taken into account while designing as well as in the process of elaborating requirements for bioturbation/penetration by organisms [34]. The potential of plants to penetrate the cover layer and create channels for the migration of some contaminants is of high importance.

4.5. Changes in the surrounding environment

Capping of the sediments results in changes in the water environment. Therefore, it is important to determine whether the potential loss of a contaminated local environment (habitat) is better than the benefit of constructing a new, modified but less polluted local environment. Ecological considerations are particularly important in relation to the top cover layer. Sand or crushed stone is often used to cover the layer of areas with fine-grained material [35]. After some time, sediment deposition and other natural processes will change the surface covering layer. Initially, changes in the organic carbon content in the cover layer material may change the nutritional behavior of organisms inhabiting the bottom in this area. A surface layer is a place of recolonization (secondary colonization), therefore it should be designed to ensure an appropriate environment for aquatic organisms. In some cases, it is possible to make an additional layer on the erosion protection layer by filling the space between materials such as ground gravel. In other cases, natural sedimentation processes after applying the cover layer can create desirable features of the local environment. For example, placing a stone layer in some river systems may lead to the surface of the cover layer similar to the existing one because the rock material can be padded with sands and mules in the process of natural sedimentation [36].

A desirable feature of ecological significance for the surface of the covering layers is, for example, the preparation of a stone ballast layer with appropriate granulation that can serve as a solid substrate to which settled mollusks (e.g. oysters, mussels) will stick. Material suitable for colonization by living organisms, such as bottom fish, may also be appropriate. A mix of smaller and larger pebbles may be desirable for the water environment in places with significant water currents. However, the risk of attracting organisms not present in the cover layer design should be considered, reducing its ability to maintain additional physical loads. In general, capping causes shallowing, which may cause the environment to be above the drain line or the lake environment may turn into wetlands. Changes in depth characteristics may be depending on the location, improve or worsen local environmental conditions for a certain population of organisms [36].

4.6. Infrastructure and waterways

Water transport capacity may decrease due to the cover layer. If the water depth decreases in the river channel or marina, the movement of some transport or recreational boats may be restricted or forbidden. The level of permissible traffic by means of water transport in the area covered by capping also depends on the fluctuation of the water level (e.g. seasonal, tidal, associated with waving) and potential effects of contact between boats and ships with a cover layer [28]. Other factors that may disrupt the integrity of the layer, such as accidental or regular anchoring of large units, should also be considered. Anchoring recreational boats may damage the cover layer.

The following aspects in the reservoir or vicinity of the water reservoir that may affect the integrity of the cover layer: water consumption, post-storm coverings or arrivals with other types of water, infrastructure nodes (land utilities), construction of bulkheads, docks and other structures damming water, excavation of material from the bottom due to navigation in the vicinity of the covering layer area, future development (construction) of commercial water transport channels in the vicinity of the covering layer [18].

Utilities (e.g. storm sewers) or its nodes (e.g. waterways, sewage, gas, oil, telephone and electric lines) are often located within waterways in urban areas. It may be necessary to transfer parts from the existing infrastructure if their failure or wear over time could harm the cover layer. Typically, however, pipes and other infrastructure are left under the cover layer, and long-term plans for operation and maintenance assume the repair and replacement of used parts. The future construction or maintenance of infrastructure nodes must take into account the existing cover layer and it may be necessary to consider a restriction of these activities by the inspection bodies if no repair is provided. The presence of the cover layer may also impose limitations on the future development of coastal structures if it is necessary to excavate material from the bottom [19].

4.7. Monitoring of capping

Monitoring of capping is required during (cap construction) and after (cap performance) construction of cap [36]. The goal is to focus on geotechnical stability of the capped sediment system, also it is of prime importance if the cap is performing the basic functions such as physical isolation, sediment stabilization and chemical isolation [36]. Furthermore, monitoring includes the use of various equipment and techniques to collect data from above and below the water surface. During the cap construction process, re-suspension (turbidity) of the sediment is necessary to control. Cap-performance monitoring usually appears during multiple events and often for a period of at least several years [36]. The following techniques and equipment should be mentioned: settlement plates to track sediment (and cap) consolidation, depth-discrete chemical analyses of bulk capping materials and cap pore waters, use of benthic flux chambers, sedimentation traps, and bioassays. Monitoring should also consider measurements of risk reduction, for example, biological chemical concentrations or biological effects or sediment, pore water, or surface water concentration reductions with time [35].

5. Modelling of capping

The following aspects of capping such as sorption, diffusion, the behavior of the aquatic sediment matrix, and the fate and transport of contaminants during landfill containment and after remediation have been carried out using various models by some researchers [37–50].

Contaminant diffusion has also been modeled by some researchers. Leo and Booker [40] developed the boundary element method for contaminant diffusion in non-homogeneous porous media. Contaminant transport in the system consisting of compacted clay liner and the aquifer using the numerical method including the finite-difference method and the numerical inversion of Laplace transform was investigated by Zhang et al. [41]. The application of analytical methods allows a better understanding of the mechanism of contaminant diffusion. For example, Chen et al. [42] proposed an analytical solution for contaminant diffusion through a multilayered system. The effect of degradation on the contaminant slowdown from sediment was also pointed out by Yan et al. [43].

Several models were implemented to sediments covered by reactive core mats playing the role of the reactive layer containing, for example, organoclay, apatite, activated carbon isolated between two permeable geotextile filtering layers [44]. In simulations conducted by Rowe [44], contaminant transport in sediments was taken into consideration. In the developed model given by Alshawabkeh et al. [45] it was found that depending on the sediment characteristics, the consolidation effect can be significant and overestimated by up to two orders of magnitude. In further studies, Meric et al. [46] measured that settlements up to 40%–60% occurred in sediments compare to the initial height. In further studies, Meric et al. [47] examined the effects and long term efficacy of reactive core mats capping on the isolation and remediation of contaminants in aquatic sediments. Meric et al. [47] developed and formulated the RCM-XPORT2 model designed to estimate the contaminant transport including the reactive cap material. The one-dimensional RCM-XPORT2 model uses the large-strain consolidation approach coupled with reactive advective/dispersive solute transport capped with a reactive core mat. The model was validated by comparing model predictions with naphthalene flux data from a consolidation-coupled contaminant transport experimental set up. The researchers proposed a hypothetical case study of pre- and post-reactive cap material application PCB fate and transport in the Lower Neponset River using the aforementioned RCM-XPORT2 and the United States Environmental Protection Agency Water Quality Analysis Simulation Program surface water quality model. It was concluded that the reactive cap material can potentially isolate the contaminants in long term and reduce the overlying water column concentrations of sediment-based contaminants.

In recent studies, Yan et al. [43] developed the analytical one-dimensional model for contaminant transport in multilayered capped contaminated sediments including the degradation of organic contaminant, diffusion and adsorption. The results indicated that the biodegradation of contaminants in the bioturbation layer has an impact on the flux at the surface system. Additionally, the thickness of the bioturbation layer influences the performance of the capped contaminated sediment. The mass transfer coefficient should be considered in designing the capping system. According to the authors, the proposed analytical model can be applied in designing sediment systems with reactive cap layers in order to verify complicated numerical methods as well as to well evaluate experimental data. However, they also indicated several limitations in applying the developed model, such as mineral dissolution ratio, the effect of temperature, non-linear adsorption and advection.

The prediction of the capping operations, for example, estimation of capping thickness can also be carried out using numerical simulation models carried out with moving barges including the velocity and dimensions of the barge [48–50]. The model of the estimation of capping thickness was applied in the Oslo harbor area where polluted sediments were dredged and then deposited. The capping layer thickness was measured by sediment profiling imaging. A prism was penetrated into the surface of the capped sediment. An image of the sediment profile was captured with a camera inside the prism. It was concluded that the model can be satisfactorily applied in using moving barges for capping operations.

6. Advantages and limitations of capping

The main benefits of applying *in-situ* capping are quick reduction of contact with contaminating compounds and, in contrast to excavated deposits, lower requirements of infrastructure needed for transport and covered with materials, their drainage, treatment and storage. A well-designed and properly installed cover layer should reduce the exposure of harmful compounds to fish and other organisms [8]. In addition, it is also a substrate for the secondary colonization of bottom organisms [34]. Changes in the shape of the bottom due to the use of the cover may cause a more suitable environment or some of the purposefully designed elements can improve local environmental conditions [20]. Another advantage is that the risk of returning to the water column of pollution and its dispersion is lower than during the *ex-situ* operation. Additionally, difficulties with the transport and storage of contaminated sediments are avoided. Most capping projects use conventional equipment and locally available materials and can be made faster and cheaper than *ex-situ* methods [18]. Furthermore, capping *in-situ* can be less disruptive to local communities than excavating sediments. Although some elements of local infrastructure are often needed for the temporary storage of materials, it is usually not necessary to use the equipment for draining, processing or storing sediments [10]. In addition, contaminated sediments are not transported via residential areas [19].

The conducted research, pilot projects and available literature in this area allow to conclude that the basic advantage of the method of covering is: high efficiency of isolation of sediments pollution over a long time, much less pollutants enter the water compare to *ex-situ* methods, devices and equipment used are widely known and materials covering the generally accessible, less destructive impact on the bottom ecosystem than sediment dredging [17]. The method is applicable after prior consideration of the following: identification of possible capping materials physically and chemically compatible with the environment in which they will be placed, assessment of geotechnical aspects along with the consolidation of the compressible material of potential interactions and compatibility between components, analyzing the method of placing the cover layer to minimize the short-term risk of release of polluted water to contaminated sediments during the application of the layer, the proper implementation of the cover layer and methods for monitoring its application and determination of long-term criteria for the integrity of the layer and its biological effects [34,35].

The main limitation of the *in-situ* capping is the fact that contaminants are left in an aqueous environment in which they can be found or dispersed if the layer is significantly damaged or if contaminants penetrate through the layer in significant quantities [36]. If the water depth is low, it may be necessary to use a protective force to protect the cover layer from damage related to boat anchoring or hooking the bottom by watercraft. In order to protect against erosion, it may be necessary to use coarse materials for the cover layer other than local fine-grained bottom materials, which can alter the biological community. Under certain circumstances it may be necessary to apply materials that will not promote colonization of the layer by formerly existing organisms, to limit damage on their part and release of underlying contaminants [34]. The further disadvantages of applying *in-situ* capping: erosive processes, this method is not convenient in shallow water areas, where the required height of the insulating layer prevents the ships from moving or when the water level rises dangerously, coverage is not applied in port channels that are regularly dredged. In addition, local conditions can affect the selection of equipment and materials, monitoring and management programs [32]. The production of gases under cover layers, especially those made of poorly permeable materials, can either generate significant lifting forces and endanger the physical stability of the cover materials above, as well as transfer some of the toxic substances through the layer [36]. In Table 3 benefits and limitations of capping are given.

7. Examples of capping applications

The first *in-situ* capping projects were completed in the U.S. in the early 1980 s. *In-situ* capping was chosen as part of remedial activities against contaminated sediments in about 15 isolation places in the U.S. [19]. In some locations, *in-situ* capping was applied as the main method, whereas in other places it was combined with the removal of sediments. Pilot studies are being conducted to examine the effectiveness of various construction and functions of various types of construction and function of top-down layers installed *in-situ* [19]. The use of a thin layer of clean material can help in returning to the natural state by covering and mixing with clean sediments when the natural rate of sedimentation is insufficient. Placing a thin layer of clean material is also used to re-fill the hollow places of previously extracted sediments, where the material mixes with the remains after extraction and reduces the risk of contamination that can occur after the extraction of sediments. In this case, the material does not work as a layer for the insulation of the covered contaminants and is therefore not considered capping *in-situ*.

As several capping projects have been performed in the U.S., two examples of various capping activities are given below [51]. The project carried out in the U.S. involves the remediation of an area formerly a San Diego shipyard with approximately 3,500 tons of construction waste. The project involved mining 35,000 m^2 of contaminated sediment from the water and its storage. As part of the task, a new structure was installed in the form of a cover layer consisting of layers of geotextile (13.5 m wide, 270 m long) sand, gravel and crushed stone to isolate remaining contaminated sediments. The cost of the aforementioned activities was about $16 million.

Another example of a capping application was conducted in Stryker Bay, located in Duluth, Minnesota (U.S.) which is a shallow flat-bottomed bay with an average water depth of 0.9 to 1.5 m (Fig. 2) [52]. Industrial activity in the area (tar and fuel production) resulted in the pollution of sediments with PAHs. Therefore, a hybrid project combining bottom dredging and application of a covering layer consisting of a sand layer and an active carbon mat (Reactive Core Mats™) was applied.

In Europe, capping activities were carried out in Belgium, Netherlands, Germany and Scandinavian countries [17,53,54]. In Norway, the first capping project was performed in the Eitrheim Bay in Sørfjorden in 1992. A difference between Norway and other countries is that in most cases capping of contaminated sediments in Norway has been conducted using marine sediments, basically in fjord and harbor areas. Since then 20–30 capping projects have been performed in Norway. These projects vary from a few thousand m^2 capped seabed to about 1 km^2 (capping in Oslo harbor).

Table 3
Benefits and limitations of capping [18,31,33–36]

Benefits	Limitations
Less intrusive than environmental dredging	Contaminants are left in an aqueous environment
Can reduce exposure of aquatic environment to contaminants in a short time	Monitoring is needed at capping sites during and after construction
Can be applied in various aquatic environments such as rivers, lakes, wetlands and harbors	Equipment is appropriate in more open areas such as harbors or wide rivers
High efficiency of isolation of sediments pollution in a long time	Strong currents can displace capping materials
Requires less infrastructure of material handling	Use of cap materials may alter the biological community
Not as expensive as *ex-situ* methods	May not be appropriate when regular navigational dredging occurs
Difficulties with the transport and storage of contaminated sediments are avoided	

In Kollevågen outside Bergen municipal waste was placed in the shoreline and in the sea in the period between 1930–1975. In 2005 the municipal waste was covered with a 0.5 m thick layer of rock material (grain size: 0–32 mm) followed by a geotextile and a 0.3 m thick erosion protection layer (grain size: 0–64 mm). Investigations in 2012 and 2014 showed that the cap was damaged and that the waste that was below sea level was exposed at several locations. The most probable reason for this was that the cap did not have sufficient stability with respect to erosion, slope stability and/or uneven settlements in the waste [55].

Another capping project was carried out in the frame of Clean Oslofjord and several areas in Oslo harbor were capped (seabed 15–20 m depth, marine clay and sand) [56]. For handling residuals after dredging several areas in Oslo harbor were capped with crushed rock (grain size 0–8 mm). Investigations of the seabed 4 y after the capping showed that in an inner part of the harbor where the ferries where docking all capping material was gone and pure grey clay from the former seabed could be seen. This was probably due to the strong current caused by the propellers of local ferries that had eroded away all the capping material. The example shows that a cap has to be designed to withstand propwash in areas with ship traffic. It also proved that areas just outside the areas that are most exposed to erosion (propwash) can withstand erosion even if the ships are moving over this area also.

The contaminated sediments in Eitrheim Bay were covered with a geotextile and capped with sand [17]. Surveys done by divers 4 y later showed that the cap was intact and there was substantial biological activity on the surface of the cap. A new diver survey and sampling of sediments 6 y later showed that the surface of the cap had been recontaminated by sources on land.

It was concluded that the reasons for that were probable: accidental and regular discharges from local industries and waste disposal. An assessment showed that a substantial increase in the concentration of contaminants in the sediments (and the cap) could take place. Fjord close to Oslo covering the deepwater disposal at Malmøykalven in the Oslo was also investigated with respect to grain size distribution. The results showed that grain size distribution in the cap corresponded to the original cap material and thereby concluding that the cap was intact.

There are some other projects with respect to capping in Scandinavian countries carried out in Denmark. A pilot-scale conventional isolation-capping project was conducted (sometimes) in the Port of Copenhagen [17]. In Finland, a creosote-impacted, 0.5 ha area of sediment in Lake Jämsänvesi was covered by a (presumably basal) polypropylene filter geotextile overlain by 1 to 1.5 m of gravel and sand [57].

Some capping activities were carried out in Sweden in fiber-rich lake sediments near stream mouth contaminated by Hg were remediated using capping [58]. The following, general description of the project included: basal geotextile overlain by ~20 cm fine-grained sand (in some areas, ~20–40 cm of crushed rock for erosion protection, in addition to or instead of the sand layer) and the capping area: approx. ~40,000 m^2.

Selected examples of capping sediments in the aspect of environment conditions (water depth, area), contaminants to be removed, capping material, application technology, long-term and short- and long-term capping performances, are included in Table 4.

In Europe, several countries work on contaminated sediments (Belgium, Germany, the Netherlands, France, Italy, Spain, Switzerland, UK). Regular workshops in the frame of the European SedNet program are organized in order to compare existing regional or national regulations with regard to their components, decision making and consequences for the catchment management [59]. Recently, it came out that the important aspect of European sediments is the lack of decision-making systems for when to clean up contaminated sites considering the Water Frame Directive or the protections of biodiversity. It was pointed out that in Europe do not exist regulations to classify sediments *in-situ* which may result in decisions on environmental dredging. There are some concepts (Belgium, the Netherlands) or under development (France) but not as a requirement in the aspect of environmental dredging. Currently, neither standards nor funding for environmental dredging exists in Europe [60]. In recent studies coming from four European countries: Norway, Sweden, Denmark and Finland the attention is paid into the status of assessments, regulations, and remediation actions of contaminated marine sediments [4]. All four countries have implemented the Water Framework Directive in addition to national regulations that provide the authority for imposing and implementing sediment remediation measures [61]. According to authors a pilot-scale conventional isolation-capping project was carried out in the port of Copenhagen [4]. The place was polluted with heavy metals, especially with mercury. Three various cap designs were tested. The authors stated that the final results and follow-up decisions are not available to the public. According to Lehoux et al. [4] after the USA, Norway is one of the world leaders in completed capping projects. Between 20 and 30 projects have been applied using various capping materials [4]. It was concluded that Norway has initiated national pilot remediation tests, followed by full-scale site remediation dredging and *in-situ* capping in several projects along the coast and Norway is the only one country among four Nordic ones that have implemented a national strategy on remediation of contaminated sediments.

8. Summary

Contaminated sediments as complex media may become a source of secondary water pollution under unfavorable natural conditions such as flood or anthropogenic, that is, dredging, construction of water structures as well as water transport. There is some evidence that capping has been more popular over the last twenty or 30 y. Amendments for sediment remediation include activated carbon, zero-valent iron, biopolymers, or apatite to manipulate chemical conditions in the environment and reduce the bioavailability of contaminants. These materials can be used directly on (or mixed into) contaminated sediments, as components in caps or within engineered mats that are placed on contaminated sediments. If the expected bottom spread and water column dispersion are acceptable conventional discharge of mechanically dredged material from barges and

Table 4
Examples of capping sediments

S. No.	Environment conditions, water depth area	Sediment	Contaminants to be treated	Capping material	Application technology	Short- and long-term and capping performances	Place/country	Reference
1	Revitalization of the former shipyard area covering the bay and land, 34 ha	Harbour	Benzene and waste from fuel production	Geotextile, sand, gravel and crushed stone	Mining 35.000 m^2 of contaminated sediment from the water and its storage	Habitat layer-grass with banded leaves – 1.6 acres of the restored environment	San Diego, U.S.	[51]
2	Industrial activity in the area of tar and fuel production, flat-bottomed bay, water depth 0.9-1.5 m, 10 ha	Harbour	PAHs One area heavily contaminated with naphthalene	Reactive core MATStm	Hybrid project combining bottom dredging and application of a covering layer consisting of a sand layer and an active carbon mat	Test columns were included to monitor the settling of material in the cover layer	Duluth, U.S.	[52]
3	Municipal waste treatment		Municipal waste	Rock, geotextile, protection layer	0.5 m thick layer of rock material, followed by a geotextile and thick erosion protection layer	Cap was damaged due to insufficient stability with respect to erosion, slope stability and/or uneven settlements in the waste	Kollevågen/ Norway	[55]
4	Seabed 15–20 m	Sea	N/A	Marine clay and sand	N/A	4 y after the capping all capping material gone due to ferries activity	Oslo harbour/ Norway	[56]
5	N/A	Harbour	N/A	Geotextile, sand	N/A	5 y after capping the surface of the cap had been recontaminated by sources on land	Eitrheim Bay, Norway	[17]
6	Lake Jämsänvesi, 0.5 ha	Lake	Creosote	Geotextile, gravel, sand	N/A	N/A	Finland	[57]
7	40.000 m^2	Lake	Hg	Geotextile, sand, rock	Basal geotextile overlay by ~20 cm fine-grained sand (in some areas, ~20–40 cm of crushed rock for erosion protection	N/A	Sweden	[58]

N/A-not analyzed.

hydraulically dredged material from hopper dredges or pipelines can be taken into considerations in the capping operations. If additional control in placement or water column dispersion should be reduced the application of diffusers or other facilities needs to be considered. Controlled discharge and movement of barges and usage of boxes with hydraulic pipelines can be considered for spreading a capping layer over a larger area. Some researchers have modeled the following aspects of capping: sorption, diffusion, the behavior of the aquatic sediment matrix, and the fate and transport of contaminants during landfill containment and after remediation. Due to the advantage that *in-situ* treatments may be relatively inexpensive compare to *ex-situ* treatments, *in-situ* capping can be a very effective option of reducing risks coming from contaminated sediments under selected circumstances. Furthermore, the method is easy to construct and can be used in the remediation of multiple contaminants and their types can be applied in various aquatic environments, such as rivers, lakes, wetlands and harbors. Additionally, capping is less disruptive for the environment than *ex-situ* methods. Capping also provides a unique habitat for faunal and floral communities and it is less disturbing to habitats with time than excavation. On the other hand, there are some limitations of applying to cap, these are: most contaminants remain in-place, capping may not be appropriate when significant erosive forces and groundwater upwelling occur, the material of capping may not be acceptable for some faunal and floral habitats and finally capping may not be effective in places when regular navigational dredging is required. There are examples of the implementation of *in-situ* capping in practice mainly in the USA and in Europe. It was concluded that in few projects capping has started functioning properly after several years but in few others, the cap was locally eroded by propellers from ships. It was also pointed out that poor conditions of soil resulted in damage to the cap due to slope failures of large settlements. In several cases, the recontamination of the seabed after capping occurred. That was the result of point sources as well as runoff from landfills from the land and/or from impervious surfaces via surface water. In recent studies of *in-situ* remediation of contaminated marine sediments (including capping), the authors concluded that there are still gaps in the knowledge about an application of *in–situ* sediment remediation technologies from both technical and practical point of view [62]. According to the data, they assumed that current techniques based on activated carbon are well developed and applied. Recontamination may also appear due to spreading from the places of the sea where remediation of contaminated sediments was not carried out. If contaminated sediments undergo for example strong currents and/or dredging the pollutants can be re-contaminated. In recent studies concerning the problem of uncontrolled resuspension especially weakly bound trace metals a new concept of the resuspension method to adsorb contaminations in sediment is proposed [63]. It should also be stated that although most *in-situ* remediation technologies including capping can be applied for various contaminants it should always be considered that the specific contaminant(s) in sediment at a site can decide about the best remediation method and designs. As there is no one particular technology appropriate for all sites. The research expands the applicability of capping but it seems reasonable to get inside fate processes in caps as well as complex biological, chemical and physical processes affecting the caps and individual contaminants in further activities.

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