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ADVANCES IN SEDIMENT SCIENCE AND MANAGEMENT

River and harbor remediation: "polluter pays," alternative finance, and the promise of a "circular economy"

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Abstract

Purpose Contaminated sediments in rivers, lakes, and harbors around the world result in diminished ecological health, degradation of environmental resources, economic losses, and, in rare cases, impacts on human health. Despite the ongoing interest in the cleanup of contaminated sediments in rivers and harbors, little progress has been made in reducing the number of contaminated sites worldwide. Proponents of a "circular economy" model assert that it can facilitate the cleanup of contaminated sediments through product and process design to eliminate waste of resources, to beneficially use (and reuse) products and materials, and to restore ecologies. This paper evaluates the application of circular economy models to practice in the treatment, removal, and processing of contaminated sediments found in waterways.

Materials and methods No materials were used in this work. Methods consisted of literature research and review.

Results and discussion Much of the difficulty in advancing the cause of contaminated sediment cleanup can be attributed to the high cost of cleanups and the difficulty in assigning financial responsibility for the cost. Simple schemes dependent on identifying polluters are fraught with underlying complexity. More elaborate approaches tied in with waterfront redevelopment show some promise but are yet to be applied routinely. New advances in the understanding of how sediments may, or may not, factor into the utility of circularity models pose new challenges and opportunities, with the potential to complement new funding paradigms.

Conclusion The most promising possibilities for achieving circularity in sediment management lie in a kind of punctuated circularity, which requires individual, project-based beneficial use opportunities. However, these ideal situations are likely to remain rare for the foreseeable future, without advancements in technology and regulatory approaches, as well as development of market demand for the products made from contaminated sediments.

Keywords Contaminated sediments · Beneficial use · Carbon reduction · Circular economy · Decontamination · Dredging · Dredged materials · Sustainability · Toxics · Waterfront revitalization

1 Introduction

The discourse surrounding "circular economy" is newly energized and offers a relatively straightforward model with appealing logic. "Circularity" in design thinking and industrial practice is intended to eliminate waste throughout supply chains and disposal, encourage continual use of resources, and promote the re-emergence of original ecologies (Ellen MacArthur Foundation 2020). Proponents argue that circularity maximizes use of inputs, minimizes terrestrial impacts, and incorporates ab initio sustainability within product and process design (or redesign) and manufacture. Although these are beneficial outcomes, the model's applicability to contribute to the cleanup of contaminated sediments in waterways[1] is unclear. Remediation requires application of defined processes and technologies to achieve stated remedial action objectives.

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[1] For the purposes of this work, contaminated sediments refer to those sediments in rivers, harbors, lakes, and other water bodies that contain sufficiently elevated concentrations of contamination to create unacceptable risks to human health or ecological receptors, thus warranting remediation.

Designers do their utmost to bring expertise and technology to improve the ecosystems at risk. Inclusion of requirements to beneficially used contaminated sediments, rather than simply remove or isolate the sediments, creates an additional challenge. How a circular economy will improve the pace or effectiveness of remediation activities is uncertain.

Cleaning up contaminated water bodies has proven to be an enormously expensive and time-consuming process. In fact, in many parts of the world, the inventory of contaminated sediments is simply ignored or perhaps studied endlessly instead of addressing the problem, avoiding the ultimate cost of remediation. Insufficient funding often directly results in prolonged study of a contaminated water body and ongoing project delays. In addition, many countries lack the legal or regulatory framework to address contaminated sediment sites (Spadaro 2011). Even in countries that address soil and groundwater contamination with some efficiency, sediment contamination is often ignored. Rhetorical arguments often suggest that the solution is as easy as "making the polluter pay." However, where applied, a singular focus on making historical polluters pay has had the counterintuitive effect of creating legal and technical complexities that ultimately impede progress toward the ultimate goal of implementing a long-term cleanup. Yet, the incentive to address sediment contamination only increases over time, with deposits of sediment contamination posing a considerable threat to water quality, the health of biota, reduction in public trust values of waterways, and, in some cases, threats to human health. Further, the need and/or desire for redevelopment of the urban and industrial waterfront is both a motivation and opportunity for cleanup. Making "potentially responsible parties" liable for remediating contaminated sites may act as a deterrent but results in extensive resistance, litigation, and debates among high-paid experts. The process ends up increasing costs and delaying remediation.

Collaboration between municipalities, ports, developers, and historical polluters can accelerate cleanups and provide collateral benefits to communities. The Great Lakes Legacy Act (GLLA) of 2002[2] is a successful example of such an approach. The GLLA encourages the cleanup of contaminated sediments through formal partnership agreements and cost sharing. Through these agreements, federal funding is leveraged with funding from state or local governments and from industry to fund remediation of contaminated sediments. The GLLA, and the projects created under its auspices, generally address not only the cleanup of sediments but also the broader community needs for redevelopment and revitalization. Through this broader approach and collaboration, the GLLA increases the involvement of the community and its role as a stakeholder in the cleanup process. This shared-funding method encourages more cost-effective resolutions and a collective sense of risk by all parties rather than the polarization of the "polluter pays" rule.

Alternatively, and perhaps consistent with thinking on circularity, another approach to addressing contaminated sediments has focused on the possibilities of beneficial use of contaminated sediments. This has been studied in various countries for over three decades (as detailed in Section 2). Were it possible to create a value-added attribute from contaminated sediments, presumably the cost of cleanup could be offset by the value of an end product, such as a specialized building material. These studies, as yet, have failed to produce a successful approach for contaminated sediments. In most cases, development of a valuable product from contaminated sediments has proven technically and/or financially impractical. In cases where the cost and technical ability were considered acceptable, the market resisted the products, preventing a profitable outcome.

In this paper, we make the case that circularity applies to dredged-contaminant settings imperfectly, if at all. We question how prescribing beneficial use, or pursuing it only reactively in specialized circumstances, constitutes circularity in any meaningful sense. We then reimagine how circularity-related principles may nevertheless come to inform and improve current approaches to remediation. In the near term, we recommend consideration of particularized conditions (what we here label "punctuated" circularity) to potentially inform some cleanups. We identify key features of such punctuated scenarios, including the application of emerging beneficial-use technologies, the summoning of collective will among polluters and regulators, and the possible economic returns from beneficially used sediments, flowing back to impacted communities and thereby helping offset the high cost of cleanup projects.

2 While circularity may be achievable for some marginally contaminated sediments, opportunities to beneficially use those more seriously contaminated will remain limited—or, who will buy bricks made of toxic mud?

The concept of applying circularity to incorporate contaminated sediments into a beneficial use methodology (now more commonly referred to as circular economy) is not new. As shown in this section, researchers and practical scientists and engineers have been evaluating the possibilities for over three decades.

[2] The GLLA was authorized in 2002 and reauthorized in 2008. Specifics about the act may be found at: https://www.epa.gov/great-lakes-aocs/about-great-lakes-legacy-act. The rules for implementation may be found at: https://www.federalregister.gov/documents/2006/05/01/06-4079/implementation-of-the-great-lakes-legacy-act-of-2002.

2.1 Attempts at sediment beneficial use strategies in the Netherlands and Germany faced limiting costs and market interests

Early investigations in the Netherlands and Germany concentrated on the financial and technical feasibility of the treatment of contaminated sediments as an alternative to placement in confined disposal facilities (CDFs).

In the 1990s, the Port of Hamburg constructed a sediment processing facility for Mechanical Treatment of Harbor Sediments (METHA) (Detzner 2007). Contaminated sediments dredged from the Port of Hamburg were treated and beneficially used as a sealing material for mounds of dredged sediments, as a substitute for clay in dike construction, and as a raw material in the manufacture of bricks and clay pellets (Detzner et al. 2004). The most successful beneficial use method applied treated sediments as a cover layer on mounds of dredged material (Detzner et al. 2004). Use of treated silt as a substitute for clay in dike construction was technically successful; however, contractors were generally unable to meet economic, legal, and ecological requirements of proposed projects[3] (Detzner et al. 2004). HZG Hanseaten-Stein Ziegelei GmbH developed a method for manufacturing bricks made of 70% treated sediments and 30% natural clay. HZG Hanseaten-Stein Ziegelei GmbH operated a factory producing these bricks using this method for 4 years. Unfortunately, this approach was unprofitable because disposing of sediments in mounds was significantly less expensive than converting the sediments to brick products (Detzner et al. 2004). Contaminated sediments were also used in the manufacture of fired clay pellets, but this process achieved only a 10 to 25% substitution for natural clay. Therefore, this technique has not been successfully applied on a large scale (Detzner et al. 2004). Additional constraints highlighted by the individuals pioneering beneficial use of contaminated sediments in Hamburg include the following (Bortone et al. 2004):

- The costs for the resulting product are much higher than the public is generally willing to pay.
- There is no available market for the resulting materials because there is low public acceptance of products manufactured from contaminated materials.
- Sustainable relocation of these sediments remains the method most in line with natural sedimentation processes.[4]

[3] Detzner et al. do not define the unmet factors. They simply say, "...no bid was submitted in the Europewide bidding procedure held in 2003 that met all the economic, legal and ecological criteria of the tender invitation" (Detzner et al. 2004).

[4] Bortone et al. state, "…untreated, relatively clean dredged material can be used, for example, for filling up deep holes, which were for instance created due to sand extraction, or just for relocating it in the river basin." While this practice is "in line with natural sedimentation processes," it is not a solution to the risk posed by the contaminated sediments. It also presupposes the existence of a suitable site for the relocation.

The Dutch government began a pilot program in 2003–2004 to evaluate the economic and technical feasibility of reusing contaminated sediments removed from the River Maas and the Gent-Terneuzen Canal during maintenance dredging events. The extent of contamination in these sediments prevents their relocation or beneficial use elsewhere without treatment; sediments of this nature would normally be disposed in a CDF. Dutch government contractors used various simple treatment methods (including dewatering, sand separation, land farming, and chemical immobilization[5]) to render sediments usable as building materials that could comply with both Dutch legal requirements and project-specific engineering requirements. The results of the pilot program indicate that the treatment and beneficial use of contaminated sediments are only economically feasible under a narrow set of circumstances. The Dutch government determined that it would not use the beneficial use strategy to address the disposal of contaminated sediments in the Netherlands. Additional limitations hindering the feasibility of beneficial use of contaminated sediments include the widespread availability of clean materials at a lower cost, project managers and contractors perceiving long-term risks associated with use of contaminated materials, and regulators treating contaminated materials as waste, which requires additional regulation and monitoring (van der Laan et al. 2007).

2.2 High costs and uncertainty of cost recovery limited alternatives to open-ocean disposal in New York-New Jersey Harbor

In the mid-1990s, concerns over ocean disposal of contaminated sediments in New York-New Jersey Harbor demanded further evaluation of treatment technologies for contaminated sediments. In 1993, New York and New Jersey state governments updated the criteria for open-ocean disposal of dredged material to maintain the navigability of the New York-New Jersey Harbor. After these new rules were in place, the majority of material removed during maintenance dredging was disposed of elsewhere, leading to a surplus of contaminated sediments and a need to develop alternatives to open-ocean disposal (Stern et al. 1998; Douglas et al. 2003). One of the successfully implemented alternatives was the use of treated dredged material as fill on brownfield and landfill sites to facilitate redevelopment of those areas (Douglas et al. 2003; Yozzo et al. 2004). The primary deterrent in employing this solution was the high cost of use as fill when compared against the cost of disposal. The increased costs were attributable to reduced material processing efficiency (resulting from both

[5] van der Laan et al. refer to mixing with cement as chemical immobilization. There is some variability in the designation of this technology as physical stabilization or solidification as opposed to chemical immobilization. We have used the authors' terminology for consistency with their work.

the diversity of material types and the inconsistent supply), the high cost of treatment and decontamination of the material, and engineering and institutional controls implemented on a site-specific basis (Stern et al. 1998; Douglas et al. 2003). Other alternatives were implemented with varying degrees of success, including the use of dredged material as fill in abandoned mine sites, construction of in-water and upland habitat, filling of dead-end canals and basins, and use of contaminated sediments as raw construction material (Douglas et al. 2003; Yozzo et al. 2004). At the time, these alternate methods were either evaluated using bench or pilot scale studies or discussed conceptually (Stern et al. 1998; Douglas et al. 2003; Yozzo et al. 2004). The primary limitations on these methods were, again, high costs and the uncertainty of cost recovery (Stern et al. 1998; Douglas et al. 2003; Yozzo et al. 2004).

2.3 Sediment beneficial use efforts in France were limited by market interest

More recently, similar to the earlier efforts in Germany described in Section 2.1, beneficial use of contaminated sediments in the form of bricks has been attempted in France. That project also evaluated an alternative method for disposal of contaminated sediments dredged during maintenance dredging events in the North of France. Specifically, this method treated dredged sediments using the Novosol®[6] treatment process, which includes two phases (Lafhaj et al. 2008; Samara et al. 2009):

1. The addition of chemical amendments to immobilize metals
2. Heat treatment to remove organic contaminants and other organic material

After treatment, the sediments were substituted at various clay-to-sediment ratios for the sand normally included in fired-clay bricks (Lafhaj et al. 2008; Samara et al. 2009). When compared against traditional bricks composed of quartz sand and clay, bricks made with a 15% sediment-to-clay ratio were sturdier and less prone to decomposition, exhibiting increased compressive strength and decreased porosity and water absorption (Samara et al. 2009). As the proportion of sediment to clay increased, the quality of brick decreased, with a decrease in compressive strength and plasticity and an increase in the porosity and water absorption (Lafhaj et al. 2008; Samara et al. 2009). Even with these variations, the physical parameters of sediment-amended bricks remained comparable with standard sand and clay bricks. At a 35% sediment-to-clay ratio, the compressive failure threshold was higher than for standard bricks (Lafhaj et al. 2008). When leaching tests were performed on the bricks, the leachate contained metals at concentrations below French federal limits, indicating that the sediment-amended bricks could technically be considered non-hazardous materials (Lafhaj et al. 2008).

The work conducted in France proves that the technology exists to make bricks from contaminated sediment but fails to address virtually all other aspects of how this technology could be successful. Is there an adequate and stable supply of contaminated sediments for brick making? Where will the brick-making factory be? Who will buy the bricks? How much will they cost? Until these answers are in hand and stable, the technology remains interesting but not practical.

2.4 In summary, previous efforts fail to present a technically and economically feasible approach to beneficial use of contaminated sediments

Beneficial use of contaminated sediments has been attempted and evaluated in numerous countries, but these attempts have been met with little success. None of the above-described efforts successfully solves for the technical, economic, and risk-perception barriers together. Bricks made of contaminated sediments have proven to be durable and effective, but they are too expensive to produce, and the market has shown a lack of interest and does not accept the risk in bricks made of contaminated sediments. As the fundamental technical, financial, and risk perception barriers remain, it is not reasonable to expect a more positive outcome in the present or immediate future.

The difficulties facing successful beneficial use of contaminated sediments are myriad. The supply of contaminated sediments (i.e., the raw material necessary for any reasonable circularity methodology) is undependable in quality, quantity, and geography. In contrast, municipal waste, sewage sludge, or biodegradable farm waste all offer reasonably reliable supply characteristics. In addition to a lack of dependability, the treated sediments or other end products are expensive and contain undesirable concentrations of the original contaminants.

A recent compilation of case studies for beneficial use of sediments (Sittoni 2019) confirms this conclusion. Of the 38 case studies that Sittoni evaluated, 18 involved some level of sediment contamination. Of these, only three addressed *remediation* of contaminated sediments; none of the three found more than minimal success. For the foreseeable future, beneficial use, and thus the implied promise of sustainability and circularity, will remain unobtainable for contaminated sediments.

[6] Novosol is a registered trademark of Solvey.

3 Polluter-pay models are plagued with legal[7] and technical difficulties

Even when a legal framework is available to force a polluter to pay for sediment contamination, identifying the polluter(s) can be an elusive and daunting task. There are cases where identification of the polluter is straightforward and the identified polluter remains a viable entity. All too often, however, the responsible parties are not present and have no viable corporate successor, resulting in so-called orphan sites (contaminated areas with no accountable party). Further complicating identification of polluters, sediment contamination can originate from non-industrial sources of contamination such as runoff from urban centers, discharges from publicly owned treatment works, or even aerial fallout from distant industrial sources. Identifying historical sources of pollution and dividing the cost of cleanup fairly among responsible parties are often time-consuming and require herculean technical and legal research and study.

Because of this generally long duration, high cost, and legalistic approach, little progress has been made in reducing the number of contaminated sites. In the USA, where the risks of sediment contamination are perhaps under the most stringent forms of regulatory management, there is painfully slow progress, and in most other countries, there is no progress at all.[8] In many cases, the actual cleanup is set aside in favor of prolonged study of the problem.

In a previous publication (Spadaro and Rosenthal 2019), we proposed instead a new paradigm for waterway cleanup and waterfront redevelopment. The new paradigm requires the vision and willingness to adopt any or all of the following strategies:

- Reframing and redefining the responsibilities for costs, including distributing more costs to those who benefit from waterway cleanup
- Encouraging municipalities and port authorities to catalyze cleanup efforts by adopting more proactive roles
- Driving real community investment through vision, leadership, and engagement
- Finding and leveraging alternative financing approaches, such as tax increment-based investments; funding for economic development, environmental protection, and sustainability; and public-interest capture of the inequitable windfalls that disproportionately benefit land speculators
- Tying some long-term investment gains to social and environmental benefits, such as ensuring that legacy residents can afford to remain in place, creating or reclaiming urban green spaces, and building resilience in the face of climate change

To further adapt this paradigm, we recommend a coordinated financial system that ties long-term gains in waterfront values to payment for sediment cleanup, which would reallocate responsibilities and invigorate community investment at the inception of the remediation process. This reimagination of waterway cleanup and waterfront redevelopment is detailed below.

4 Contaminated sediments and beneficial use: imagining moments of punctuated circularity

As demonstrated above, applying circular economy principles to remediation of contaminated sediments in rivers, ports, harbors, and other water bodies faces limitations. The pursuit of a more circular economy and its goals of mutually beneficial manufacturing efficiency and environmental management is laudable and seems effective, in principle. Within defined parameters, circularity can be achievable and benefit society. However, as we have done our best to demonstrate, the parameters undergirding circularity apply to contaminated sediments imperfectly, if at all. That said, there is intense interest within the contaminated sediments field in viewing traditional questions through a renewed, more circular lens. In that spirit, we wish to proceed onward from our general assessments stated above, to imagine situations and contexts where the vision of sustainable use of dredged material with contaminants is, perhaps, more attainable. To accomplish this, we look toward adapting circular thinking as best we can to fit the realities of current practice. We develop idealized conceptions of circularity—what we call prescriptive (by design), and reactive (by necessity)—and identify a feasible combination of plans and actions we denote as "punctuated" circularity.

In its typical application, circularity means to redesign manufactured products, making the use of natural resources more self-contained, environmentally responsible, and sustainable. The conceptual goal of a circularity is the "take-make-waste extractive industrial model"[9] (Ellen MacArthur

[7] This work takes note of the legal issues associated with the polluter pays approach but offers no legal advice.

[8] The authors are unaware of statistics comparing completed sediment remediation projects to the country-specific or global backlog of sites. However, it is well accepted that the remediation of these sites is lengthy and is fraught with difficulty. For example, the Portland, Oregon, Superfund Site was listed in 2000 and is likely 20 years (at least) from completion of cleanup. The Portland Harbor case is not an isolated example. Similarly, long durations are observed for many other remediation projects in the USA. Outside the USA, it is even harder to draw comparisons because many countries do not publicly list contaminated sites. In instances where they do, such as in Italy, lengthy durations similar to those found for remediation sites in the USA are reported. In Italy, there were 57 Sites of National Interest in 2012. Today, there are 41, but most of the reduction has been the result of changed criteria for listing, not the result of successful remediation (ISPRA 2020).

[9] Extractive, linear "take, make, waste" processes are sometimes also called "take, make, dispose." Proposals to make processes "circular" attempt to design toward beneficial use not disposal. See Lacy et al. 2020.

Foundation 2020). This model is based on ecological research and technological redesign, emphasizing three principles (Ellen MacArthur Foundation *op. cit.*):

- "Design out waste and pollution"
- "Keep products and materials in use"
- "Regenerate natural systems"

In a decentralized market system influenced by price signals, keeping products and materials "in use" assumes the existence and practicality of complex supply-demand interactions among buyers and sellers. Proponents of a circular economy envision a world where the behaviors of suppliers of inputs, manufacturers turning those inputs into products, and end users of these products converge and reinforce one another. Producing and marketing products marked "sustainable" or "organic" does not guarantee that buyers will want them or demand them at sufficient volumes for a given set of prices. There is little doubt that forms of environmentally responsible exchange are feasible across several sectors. But, as we have demonstrated, it is unrealistic and infeasible to introduce the dangerous pollutants present in industrial ports, harbors, and canals into end products through a circular economy.

Figure 1 below depicts a circular economy where contaminated sediments are employed in producing masonry materials for construction projects. These bricks composed of toxic mud would enter the market through beneficial use of disposed sediments. However, these toxic-mud bricks would compete with traditional bricks lacking such a label. If or when the toxic-mud bricks manage to prevail in the marketplace (however unlikely that may be), their presence would displace demand for traditional bricks, allowing the raw materials used to make traditional bricks to remain unused in the environment. Under these terms, the circular model would theoretically result in conservation of resources. However, for this to be possible, new beneficial use technologies would have to be designed; that process would require risky financial investments all on its own, with little guarantee of technical feasibility in advance. Each such instance carries with it a benefit-cost calculus both for the industry stakeholders involved and the public health.

Circularity is a flexible concept, challenging professionals to apply it toward our fields of practice in whatever ways possible. As a result, circularity has become a source of fascination in the contaminated sediment professions, among a community of accomplished and esteemed colleagues. Therefore, as much as we may question circularity's immediate, feasible application in the world of contaminated sediments, identifying how circularity can be applied to sediment remediation on an individual and project-specific basis can be advantageous for our industry.

If professionals in sediment management and remediation adopt circularity thinking, it may encourage the needed innovation and the identification of projects where circularity and beneficial use is appropriate. In some cases, treatment and beneficial use of contaminated sediments may be mandated (*prescriptive circularity*).[10] In other cases, project stakeholders and participants may respond to the particularized needs and opportunities presented within specific projects by pursuing beneficial use (*reactive circularity*) (e.g., a given project's scientists and engineers might ask one another, "We've got a load of usable sediment sitting in this waterway; can we *do* something with it?"). At the very least, the professions' adoption of circular thinking might energize the needed innovation and the identification of projects where it would make sense. In a fully circular world to come, contaminated sediments may not even be addressed until a viable beneficial use is identified as part of the original extraction and its justification. We are not optimistic these conditions can simply be declared by regulators or concocted by project personnel and stakeholders in widespread applications, especially where contaminated sediments present serious impediments. But envisioning how the field can make progress on beneficial use in the future is arguably worthy of at least some vision and reflection.

To better understand how circularity can apply to contaminated sediment remediation, we must define uses of circularity in the field based on circularity principles, outlined here as *prescriptive circularity*, *reactive circularity*, and, the principle that most accurately captures cleanup-project realities, *punctuated circularity*:

Prescriptive circularity involves a prescribed set of conditions, imposed through a mix of voluntary industry standards and coercive regulatory gestures. Government can also signal interest in promoting circularity across the economy generally; one example is the recent policy directive from the government of the Netherlands (Dijksma and Kamp 2016). (We are informed that this policy directive is now influencing practice in a number of fields, even sediments, despite the fact that the document does not address sediments in any specific way.) Once new beneficial use standards are piloted, and their feasibility is better understood, they can become more familiar to practitioners and more frequently met. Although we are reluctant to believe that idealized standards can change project conditions and technological constraints by themselves, they can signal best-effort expectations that change how things are done. Responsible redesign occupies this realm, as it must; the notion that brighter minds envisioning future improvements can re-engineer systems necessarily requires that they can command the reform of those systems. Prescribed circularity has succeeded in the context of supply chains, particularly where a progressive bulk purchaser of goods can mandate or

[10] Indeed, regulators and policy makers can adopt circularity in at least two ways: as a general principle or as a detailed set of required evaluative, design, and procedures to be implemented in every remediation plan.

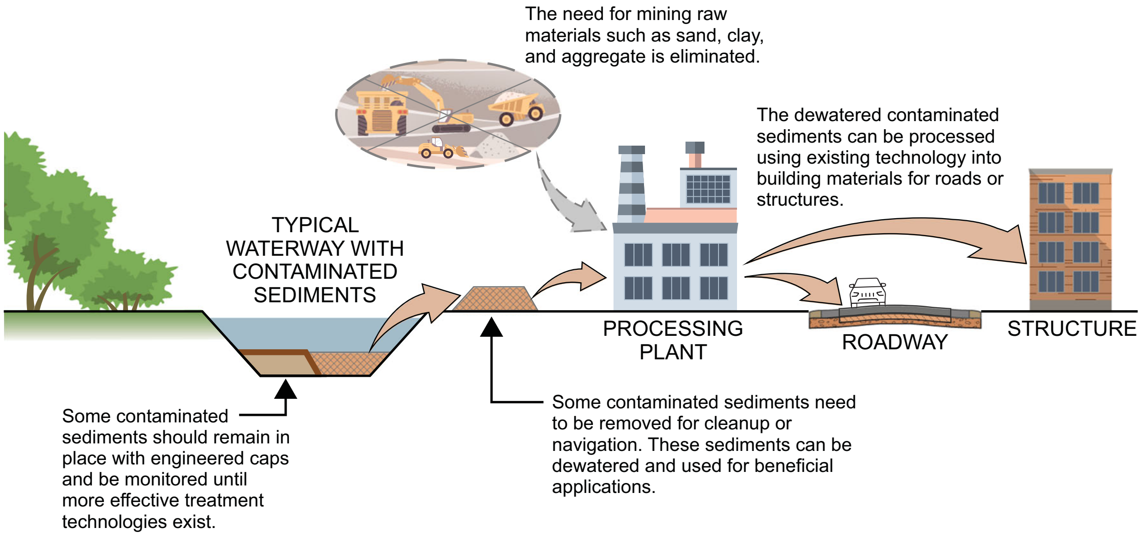

Fig. 1 Example of a circular economy where contaminated sediments are employed in producing masonry materials for construction projects

regulate the desired change. For example, a wholesale purchaser can inform producers that its future purchases will depend upon implementation of new manufacturing regimes. That is, Walmart can tell milk producers they will lose its business if they do not adopt aggressive carbon reduction steps (Mui 2007), or Levi Strauss can make its supplier lists transparent and tell remote garment factories abroad that renewal of their contracts depend upon reform of their labor practices (Doorey 2011). Implementing these prescriptive changes to production processes will often cost more for bulk purchasers. In the same way, prescriptive circularity in the contaminated sediment context will depend, in part, upon involved parties having a willingness to absorb higher prices. To successfully apply prescriptive circularity in an economy and achieve a social good (i.e., to set such a standard and actually meet it) will often require such risk taking, regardless of how sensible the changes may seem in principle. It is important that discussions of circular redesign for contaminated sediments confront cost changes, technological constraints, and participants' incentives.[11]

Reactive circularity shifts the focus from regulated standards to project specifics. The few moderately successful examples of beneficial use we have reviewed in this paper (e.g., using treated New York-New Jersey dredged materials in fill applications elsewhere) occurred when within-region opportunities were identified and compared with alternative modes of disposal. Project-level reaction in sediment remediation involves understanding how future systems for treating contaminated sediments and using the resulting material can best work under current conditions. Even in a circular economy, malfeasance and mistakes will occur, and cleanups will remain necessary. Unplanned deviations such as these, by their very nature, require reactive engineering. Contaminated sediments in waterways present management problems that are site specific. They do not fit well with how circularity conceptualizes origin-driven resource sustainability. Outside the harvesting of natural radiological stores for industrial application, an example where circular thinking is much needed, the circular economy models we have seen in the manufacturing context rarely address, if ever, the issue of disposing of industrial-byproduct contaminants. Technological advances may eventually make beneficial use of contaminated sediments possible. However, despite 30 years of beneficial-use analysis, the necessary and desired innovation has not come to fruition. Instead, slack industry and governance resources have been spent on wasteful adversarial efforts to enforce polluter-pays principles. Despite these historical setbacks, there remains hope that lower-cost conversion technologies will be developed. Unless and until that happens, however, we are unlikely to see significant investment expanding beneficial use of contaminated sediments. For our industry to realize the promise of circularity, it must find ways to ensure that the economic costs of recovery remain less than the economic value of what is recovered (CR < VR). Applying circularity models in sediment remediation will likely remain limited to individual, project-specific opportunities, and industry-wide progress on beneficial use will remain elusive at best. Therefore, it is necessary to aim toward maximizing gains in project-specific, punctuated ways.

Punctuated circularity involves adjusting contaminated sediment practices in ways that embody circular economy fundamentals. From a golf course produced with dredged material in the Port of Oakland to more recent experiments using treated dredged material in port-slip refill (e.g., Tomley 2016), the opportunities are situationally constrained, requiring creative thinking. For the

[11] One referee during the *Journal*'s review of this article emphasized the necessary role subsidy will often play, relative to state involvement in circularity-policy decisions and rules. We agree.

foreseeable future, every opportunity for punctuated circularity will involve a pilot experiment necessitating long-range monitoring of downstream effects. More than the fully engineered, prescriptive cases of circularity, and the one-off reactive ones, successful application of punctuated circularity takes longer-range vision and adaptability. We accept and endorse the concept that sediment management and treatment can be combined with the evaluation of potential sediment placement and use. Unlike the dispersed benefits of circularized manufacture and production, the fixed locations of real-world cleanup projects mean that the costs and benefits of contaminated sediment use are regionally concentrated. Spatial characteristics further distinguish the case of contaminated sediments from the product-redesign emphasis of typical circularity applications. Every traditional cleanup project setting has its own sedimentary features, hydrology, and geosocial context. Punctuated circularity must meaningfully address the specifics of each situation. In cases we have summarized in recent work, a key requirement for successful application will be to ensure that communities historically burdened by disrupted ports and harbors will be the ones to reap the long-term benefits of remediation projects. For example, were economically beneficial uses to be found for the dredged contaminated sediments in the Gowanus Canal, circularity would require that some portion of that benefit be redistributed directly to the community and neighborhoods surrounding the contaminated area. This would help the community absorb both historical effects on its economy and environment and the remediation costs to come. Applying punctuated circularity to sediment remediation, we argue, requires (1) risk-adjusted estimation of the proposed use's total benefits and costs, (2) institutional commitments ensuring the feasibility of circular project features, and (3) commitment to equitable compensation for local communities, ensuring that they benefit to the greatest extent possible.

In current practice, prescriptive, reactive, and punctuated processes may partially overlap. Any given project may have phases of each. That said, with regard to contaminated sediments, we believe punctuated circularity is the most useful of the three. Progress toward beneficial use is necessarily constrained by fixed limits on our capacity to convert toxic sediments into materials safe, useful, and reliable in all instances. Longstanding engineering and design practices often determine that profoundly compromised waterway soils should be capped and left in place, not dredged for beneficial use. Indeed, the traditional practice of confinement, still appropriate in many instances, provides a useful counterfactual to the circularity-driven suggestion that all disposed waste can and should be processed and used. However, circularity considerations can be instituted promptly upon initiating cleanup and reclamation projects by asking the very questions circularity economists ask in other industries:

- How will long-term sediment impacts, such as possible human exposure to contaminants remaining in dredged and treated material, be predicted and managed?
- How can the *origin loci* of resources (the human communities nearby) become structurally invested in managing these downstream consequences and benefiting from the economic value of dredged sediment beneficial use?
- What processes govern adaptation and compliance once design is circularized?

We see an example of such punctuated circularity in the world of transportation infrastructure. The renewal of the highway grid, even if it is to be traversed more and more by electric and even autonomous vehicles (Todorovic et al. 2017), will necessitate roadway restoration. Road-bed application of contaminated soils has been attempted and may be worthy of further exploration in the context of dredged sediments. A two-step stabilization and solidification process for the sediments reduces leachability of contaminants, and surface paving can act as a cap (Mater et al. 2006; EPA Region 2 2017). Study of dredged-sediments and use in road-bed construction is still in its early stages, both in terms of technical feasibility (mechanical) and its eventual environmental performance. The *sedimateriaux* approach devised at the University of Douai (France) shows great promise, concentrating on road underlays, paved shoulders, and technical backfill for road and shoulder infrastructure (Foged et al. 2007; Abriak et al. 2015).

For now, singular cleanup projects would need performable commitments for such road-bed use to be a viable alternative to the typical treatment-disposal placements. Unless government leads the way by enacting and updating regulations, requirement-waivers would need to be obtained on a punctuated, project-by-project basis. Meanwhile, transportation authorities and road-bed contractors would have to commit to such uses in lieu of traditional aggregates and other materials. Because high transit and treatment costs keep beneficial use of sediments from being competitively priced compared with customary road-bed construction supplies, subsidy and accompanying regulatory conditions cannot be avoided.

More generally, market behavior often will be difficult for circularity designers to alter. We can design sediment use and market the resulting products. If they are not demanded in substantial quantities compared with cheaper, less circular alternatives, we will not attain the social objective absent substantial subsidy and/or direct procurement of such products by government. Public investment of this sort is rather more likely to occur where there are precedents (e.g., among some EU members) than where there are not (e.g., the US). These transactional realities limit the application of circularity concepts across the board.

5 Summary and suggested approach

Contaminated sediments in rivers and harbors present a difficulty to resolve environmental, social, and economic issue. The polluter-pays approach has largely failed to achieve the presumably desired effect of reducing the inventory of contaminated sediment sites. When beneficial use can be economically beneficial, the returns must be incorporated into the financing of cleanups. Further, those communities suffering the greatest losses due to the original contamination are entitled to receive profits and benefits produced in the process.

Harmonizing extraction and end use, in the case of contaminated sediments, will not occur absent investment and leadership. We see no path forward without substantial subsidy and collective (public) risk management. Existing cleanup regulation invariably leads to adversarial legalism, exorbitant costs, and delays approaching permanent disregard, grand plans stuck in the toxic mud. It is difficult to prioritize circularity in this realm, when addressing the backlog of contaminated sites takes precedence.

Currently, market actors lack sufficient incentives to carry the commercial risk involved, especially among potentially responsible parties. To fulfill a more circular vision of how remediation can work in the context of circularity, government's role will have to transform. Regulatory agencies must mediate not only the design, financing, and liability for safe sediment removal and treatment, they must become insurers of cutting-edge experiments in beneficial sediment use and related technologies. Through punctuated circularity, we envision federal- and state-level participation working in conjunction with local leadership. A restored port has future economic value, and those returns will manifest locally and regionally. The future economic value of a restored and enhanced waterway, along with that of adjacent real estate and neighboring commercial activity, can be leveraged in support of this kind of investment. Measured borrowing against future gains generates a virtuous cycle: perhaps this is the readiest variety of circular thinking applicable to realities of contaminated sediments.

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