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REMEDIATION OF CONTAMINATED SEDIMENT: A WORLDWIDE STATUS SURVEY OF REGULATION AND TECHNOLOGY

ABSTRACT

The remediation of contaminated sediment is becoming more common throughout the world. Ongoing remediation projects can be found in Israel, Brazil, Australia, and numerous European countries, as well as at many sites throughout North America.

Given this situation, now seems to be an appropriate time to reflect on the current status of this field and the variety of approaches currently in use around the world.

In particular, the following should be considered:

- What countries currently have a regulatory framework in place?
- What countries currently have a technical framework in place?
- What technologies are in active use?

Through this status survey, we can develop a "snapshot" of the current state of the industry and evaluate the need for and value of additional development of approaches and technologies.

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INTRODUCTION

The regulatory and social mandate to address contaminated sediment is growing. As members of the community of professionals on the inside of the world of sediment management, we observe this growth from a unique perspective. As recently as the 1980s, environmental issues such as contaminated sediment management were not a welcome addition to the agenda in the view of many dredgers, port operators and others on the waterfront.

This resistance seems almost inconceivable today, when this issue has become such a critical element of our inward conversation (amongst those working within the dredging community) and our outward conversation (with the public and the regulating community).

Now it is 2011. The issue of contaminated sediment management has gained a permanent place in our thinking about the waterfront.

Above: Remediation of the Pine Street (Burlington, Vermont USA) site was accomplished using a reactive core mat to prevent seepage of coal tar. Such remediation projects of contaminated sediment are becoming more common throughout the world.

Technologies including capping, monitored natural recovery, and dredging have advanced and continue to develop. At the same time, contaminated sediment management has differentiated itself from the mainstream industry of dredging.

While we (the scientists and engineers dedicated to the management of contaminated sediments) have worked diligently to understand the potential environmental consequences of dredging as well as the other technologies, have also struggled to show the important benefits to society of capital and maintenance dredging and how the positive attributes of dredging, such as benefits to commerce and coastal defense, can and do balance the risks.

And while this debate has continued, related concerns surrounding the occurrence and extent of ecological and human health risks of contaminated sediment have continued to grow. These concerns were barely recognised three decades ago (with a few notable exceptions). Now, we face ever-increasing attention and mounting expenditures in the private and public sectors to address them.

It is not the objective of this work to debate the points made by others about the technical or regulatory merits of sediment remediation. Nor is it the objective to further the discussion of the environmental consequences of capital or maintenance dredging or the regulation of dredging itself. Rather, it is the objective here to observe the situation and document the current conditions.

GROWTH OF THIS FIELD

Frightening stories of sediment contamination have been with us for about half a century. The relationship between sediment contamination and human disease was recognised as early as 1956 (Ministry of the Environment – Japan 2002), when mercury poisoning from the ingestion of contaminated fish and shellfish was identified as the source of Minamata disease.

In the late 1970s, despite dramatic improvements in water quality, significant problems in benthic and epibenthic ecology began to surface. The research of Varanasi and others (Varanasi *et al.* 1985; Malins *et al.* 1985) clearly established the link between sediment contamination and lesions and other abnormalities in fish.

A series of dredging crises unfolded in the United States over the years starting in 1985 at Four Mile Rock in Seattle, Washington (Urabek and Phillips 1992), progressing to New York in the mid-1990s (Spadaro 1997), and continuing to this day in the ports of Cleveland and Toledo, Ohio (Great Lakes Maritime Task Force 2007).

In the United States, an entire industry related to the cleanup of contaminated sediment at Superfund sites has developed and is thriving.

The regulatory mandate to address contaminated sediment as a distinct environmental medium worthy of cleanup has been with us since the late 1980s. However, the primary triggering event for concern or cleanup can often come from the redevelopment of waterfront infrastructure, capital or maintenance dredging programmes, or concerns about the contamination of fisheries resources.

As a result, each year sees a new regulation relating to contaminated sediment being published by a national, regional, provincial, state, or local government.

As we enter the second decade of the 21st century, the concern about contaminated sediment is growing. Large- and small-scale studies are in progress in numerous countries. Cleanup projects, particularly large and complex ones, are becoming more common. But how common? In what countries? According to what rules? Using what technologies?

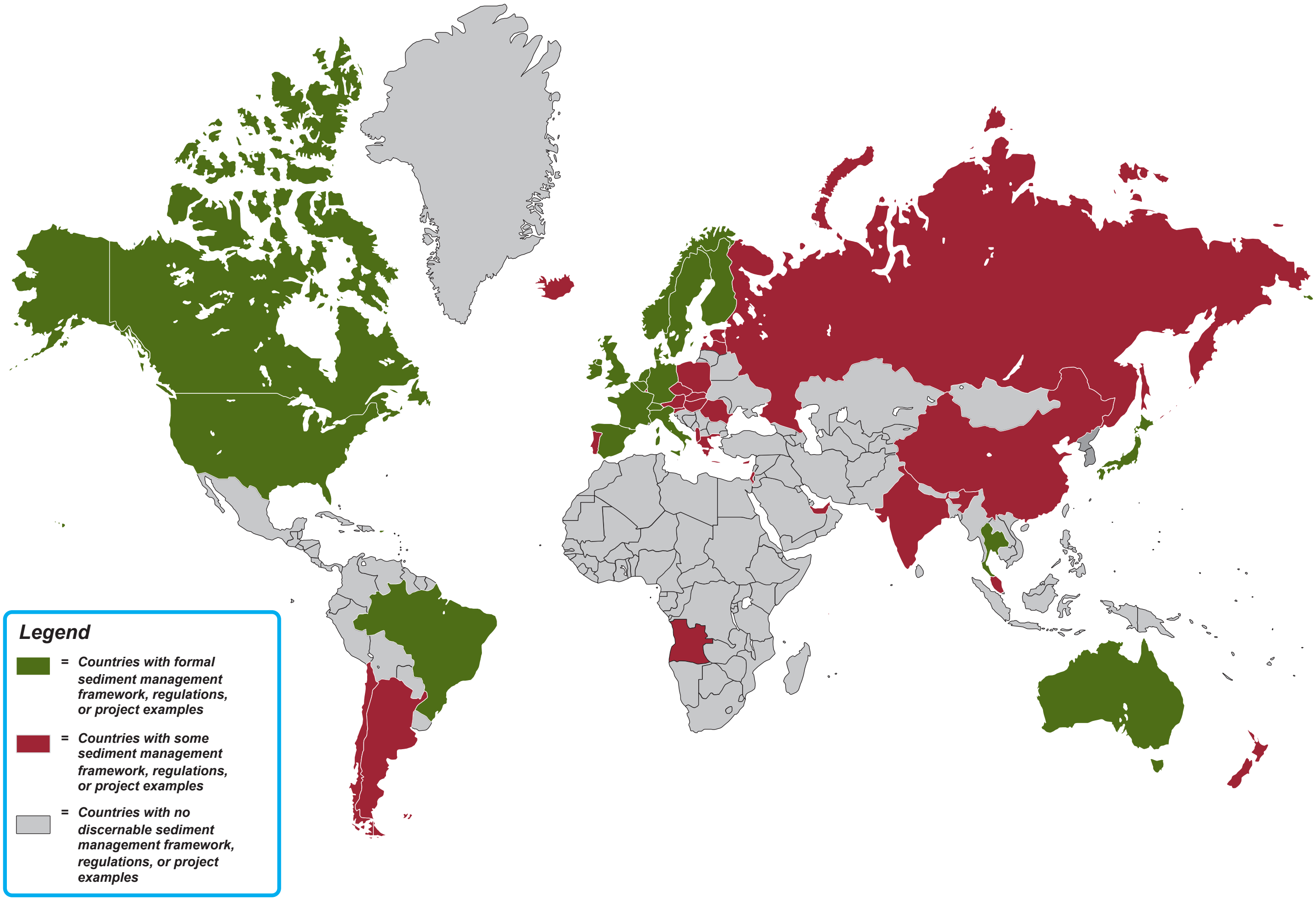
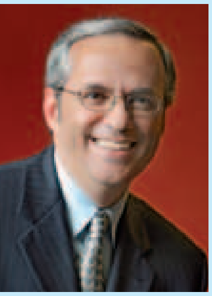


Figure 1. Global map identifying regulatory and technical findings.

Table I. Country Listing and Internet Search Results

Country	Search Result	Country	Search Result	Country	Search Result	Country	Search Result
United States of America	239000	Venezuela	9840	Oman	5180	Sierra Leone	3550
Canada	133000	Nigeria	9700	Syria	5180	Somalia	3550
United Kingdom	106000	Kenya	9540	Serbia	5120	Gabon	3520
Germany	85400	Monaco	9390	Mali	5100	Yemen	3520
China (PRC)	76900	Bulgaria	8930	Papua New Guinea	5080	Liberia	3450
Japan	74800	Iceland	8510	Malta	5050	Moldova	3370
Australia	70700	Iraq	8260	United Arab Emirates	5050	Rwanda	3360
Netherlands	67900	Niger	8210	Uruguay	5030	Cape Verde	3310
Mexico	65400	Ukraine	8020	Mozambique	4870	Burkina Faso	3270
France	65000	Slovakia	7970	Namibia	4870	Suriname	3270
India	44500	Panama	7770	Bahamas	4840	Saint Kitts and Nevis	3250
Italy	44300	Costa Rica	7560	Bosnia and Herzegovina	4840	Democratic Republic of the Congo	3200
Spain	42800	Jamaica	7160	Cameroon	4800	Seychelles	3190
Sweden	42400	Saudi Arabia	7000	Marshall Islands	4780	Liechtenstein	3110
New Zealand	35700	Morocco	6950	Zambia	4750	Tonga	3110
Russia	34100	Tanzania	6880	Madagascar	4740	Micronesia	3100
Switzerland	33800	Croatia	6850	Latvia	4670	San Marino	3050
Brazil	31700	Kuwait	6840	Nicaragua	4650	Bhutan	3030
Belgium	27200	Slovenia	6810	Central African Republic	4560	Antigua and Barbuda	2990
Norway	26800	Cuba	6790	Fiji	4560	Brunei	2980
Denmark	26600	Ghana	6700	El Salvador	4530	The Gambia	2970
Poland	25200	Sri Lanka	6690	Burma (Myanmar)	4460	Mauritania	2940
Turkey	23100	Nepal	6560	Congo (RoC)	4380	Equatorial Guinea	2870
Ireland	21500	Bolivia	6410	Honduras	4380	Swaziland	2830
Greece	19200	Ecuador	6380	Albania	4370	Maldives	2790
Chile	19000	Sudan	6270	Armenia	4350	Kyrgyzstan	2750
Finland	18400	Estonia	6250	Botswana	4320	Palau	2720
South Africa	18300	Ethiopia	6130	Angola	4300	Kosovo	2700
Austria	18100	Lebanon	5940	Dominican Republic	4260	Tajikistan	2660
Portugal	18100	Haiti	5860	Guyana	4190	Côte d'Ivoire	2630
Taiwan	18100	Uganda	5850	Malawi	4120	Turkmenistan	2630
Argentina	17400	Chad	5840	Libya	4100	Burundi	2620
Thailand	17000	Luxembourg	5790	Belarus	4070	Eritrea	2570
Israel	16600	Mongolia	5770	Azerbaijan	4040	Vatican City	2540
Vietnam	15100	Tunisia	5660	Grenada	4040	Dominica	2520
Indonesia	14700	Cyprus	5650	Uzbekistan	4040	Lesotho	2510
Malaysia	14000	Cambodia	5640	Belize	4000	Vanuatu	2430
Singapore	13500	Trinidad and Tobago	5600	Paraguay	3990	East Timor	2360
Egypt	13200	Kazakhstan	5590	Barbados	3980	São Tomé and Príncipe	2160
Bangladesh	12000	Zimbabwe	5560	Mauritius	3950	Djibouti	2100
Czech Republic	11900	Guatemala	5550	Macedonia	3890	Comoros	1990
Hungary	11800	Afghanistan	5540	Palestine	3820	Guinea-Bissau	1930
Philippines	11800	Senegal	5490	Bahrain	3780	Kiribati	1890
Romania	11000	Lithuania	5440	Montenegro	3780	Tuvalu	1810
Peru	10900	Samoa	5360	Solomon Islands	3730	Nauru	1630
Colombia	10300	Algeria	5230	Benin	3710	Andorra	1490
Pakistan	9870	Saint Vincent and the Grenadines	5220	Qatar	3680		
Iran	9850	Laos	5190	Saint Lucia	3670		



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APPROACH

Search criteria were developed for generating an informal Internet "snapshot" of the state of contaminated sediment issues around the world in 2010. For each of 196 countries (the 192 member states of the United Nations plus Kosovo, Palestine, Taiwan, and Vatican City), a phrase in the format of "country + contaminated sediments" was searched, and the number of results was recorded. Results for this type of search are of course qualitative and time-dependent.

The searches were conducted over a few days in March 2010 so the results would be contemporaneous and internally consistent. The tabulated results are presented in Table I.

Using the results from these initial searches, key documents were identified and reviewed to address the larger regulatory and technical questions. The results of this review are presented in Table II and depicted graphically on Figure 1. The figure and tables are color coded to indicate countries with both regulatory and technical frameworks (green), countries with one or the other (red), and countries with neither (gray).

FINDINGS

Internet search results vary from a high of 239,000 (United States of America) to a low of 1,490 (Andorra). The results make intuitive sense, with countries having well-known sediment management programmes producing more Internet search results. No allowances were made for size of country, length of coastline, or degree of industrialisation. The searches were conducted only in English. Testing the results with a comparable nonsense search phrase suggests that results of 10,000 or less generally indicate little or no sediment management activity within a country. Results of 6,000 or less appear to be "noise" in the search results.

Quality standards related to dredging

As of March 2010, about 35 countries appear to have some type of regulatory framework relating to contaminated sediment management, primarily in the form of environmental quality standards related to dredging. Many of these frameworks are relatively new, appearing to have been promulgated within the past decade.

And only a few of them appear to be more than guidance; strict requirements for cleanup are not prevalent. About the same number of countries (largely, but not exclusively, the same countries) appear to have some type of technical framework available to evaluate risks from sediment contamination.

The technologies employed tend significantly toward removal (dredging) and off-site disposal. A small minority of countries appear to be intentionally employing techniques other than dredging, such as capping or monitored natural recovery (Figure 2).

OBSERVATIONS

Although we have made significant progress over the past 30 years, the challenges seem daunting. We are still struggling to find the best way to apply a scientifically sound, risk-based approach to the screening and cleanup of contaminated sediment sites. A diversity of approaches exists and these are often used and sometimes combined in less than scientific ways.

In many cases, guidance on concentrations intended for screening of sites is applied as clean up criteria resulting in overly conservative approaches. We are engaged in a debate over the relative merits of the watershed approach to contaminated sediment management (Apitz *et al.* 2006) and an approach more focussed on cleanup of sediment contamination hot-spots. The former approach articulates the value of management of sediments within an entire watershed in mind while the latter approach seeks to address sediment contamination on a smaller scale, typically in proximity to legacy sources of industrial pollution. Thus far, we have not found a highly effective and reasonably priced "silver bullet" technology for sediment treatment (Van der Laan *et al.* 2007).

New contaminants, such as personal care products and pharmaceuticals, are presenting themselves faster than we have been able to address the classic contaminants of mercury, polychlorinated biphenyls, and pesticides. And the more experts press for source control to prevent the recontamination of sediment after cleanup, the more the realisation dawns that the runoff from our agricultural and urban settings, as much as from any industry, is also responsible for sediment contamination.

Figure 2. Remedial design at the Thea Foss Waterway, Tacoma Washington, USA included evaluations of source control measures and potential disposal sites, natural recovery analysis, cap, dredging and confined disposal facility designs, a hydrographic survey and habitat mitigation plans.

Table II. Summary of Characteristics by Country (for abbreviations see page 21)

Country	Regulatory Framework	Scientific Framework	Technologies Employed[1]	Search Result	References
United States of America	Yes	Yes	d, c, nr, ss, sp, it, et, b	239000	Linkov 2006
Canada	Yes	Yes	d, c, nr, ss, sp, it, et	133000	Canadian Council of Ministers of the Environment 1999, 2001, Sydney Tar Ponds Agency 2010, British Columbia Laws, 2003
United Kingdom	Yes		d, c	106000	Brewer 1997
Germany	Yes	Yes	d, c, ss, l, sp, it, et, b	85400	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 1998, Löser 2001
China (PRC)	Unknown	Yes	d	76900	Liu 1999, Chen 2007
Japan	Yes	Yes	d, c, ss, sp, it, et	74800	Ministry of the Environment - Japan 1994, Hosokawa 1993
Australia	Yes	Yes	d	70700	Department of Environment and Conservation, 2003, Guerin 2001, Rae 2006, New South Wales Consolidated Acts, 1997
Netherlands	Yes	Yes	d, c, nr, ss, l, sp, it, et, b	67900	Ministry of Housing, Spatial Planning and the Environment 1998, 2009
Mexico	Unknown	Yes	Unknown	65400	Gomez-Alvarez, 2007
France	Yes	Yes	d, c	65000	Poirier 2007
India	Unknown	Yes	Unknown	44500	Jumbe 2009
Italy	Yes	Yes	d, c, l	44300	Carere 2008, DiTermini, 2008
Spain	Yes	Yes	d	42800	Garg 2009
Sweden	Yes	Yes	d, c, it, et, b	42400	Hultsfreds 2010, Projekt Turingen 2003
New Zealand	Yes	Unknown	Unknown	35700	Ministry of the Environment – New Zealand 2009, 2010
Russia	Unknown	Yes	d, c	34100	Koukina 2003, Dauvalter, 2006
Switzerland	Yes	Yes	d	33800	Wildi 2004
Brazil	Yes	Yes	d	31700	Amorim 2007
Belgium	Yes	Yes	d, c, nr, ss, l, sp, it, et, b	27200	Vervaeke 2003, Goethals, 2001
Norway	Yes	Yes	d, c, ss	26800	Norwegian Council on Contaminated Sediments 2006, Barton 2008, Ministry of the Environment – Norway, 2004
Denmark	Yes	Yes	d, c, ss	26600	Sear 1996
Poland	Yes	Yes	Unknown	25200	Aleksander-Kwaterczak 2008, Kuperberg 2001
Turkey				23100	
Ireland	Yes	Yes	Unknown	21500	Environmental Protection Agency – Ireland 2008, Brogan 2002, Jarvis 2006
Greece	Yes	Unknown	Unknown	19200	
Chile	Unknown	Yes	Unknown	19000	Godoy-Fáundez 2008
Finland	Yes	Yes	d, c, ss, sp	18400	Ministry of the Environment – Finland 2008, Londesborough 2005, Dauvalter 2006
South Africa				18300	
Austria	Yes	Yes	Unknown	18100	Liska 2008
Portugal	Yes	Unknown	d	18100	
Taiwan				18100	
Argentina	Unknown	Yes	d	17400	Andrade 2002, Ronco 2008
Thailand	Yes	Yes	d	17000	Panichayapichet 2006
Israel	Unknown	Unknown	d	16600	
Vietnam				15100	
Indonesia				14700	
Malaysia	Unknown	Yes	Unknown	14000	Praveena 2007
Singapore				13500	
Egypt				13200	
Bangladesh				12000	
Czech Republic	Yes	Unknown	Unknown	11900	
Hungary	Yes	Unknown	Unknown	11800	
Philippines				11800	
Romania	Yes	Unknown	Unknown	11000	
Peru				10900	

Continuation Table II.

Country	Regulatory Framework	Scientific Framework	Technologies Employed[1]	Search Result	References
Colombia				10300	
Pakistan				9870	
Iran				9850	
Venezuela				9840	
Nigeria				9700	
Kenya				9540	
Monaco				9390	
Bulgaria				8930	
Iceland	Yes	Unknown	Unknown	8510	
Iraq				8260	
Niger				8210	
Ukraine				8020	
Slovakia	Yes	Yes	Unknown	7970	Apitz 2006
Panama				7770	
Costa Rica				7560	
Jamaica	Unknown	Yes	Unknown	7160	Knight, 2004
Saudi Arabia				7000	
Morocco				6950	
Tanzania				6880	
Croatia				6850	
Kuwait				6840	
Slovenia	Yes	Unknown	Unknown	6810	
Cuba				6790	
Ghana				6700	
Sri Lanka				6690	
Nepal				6560	
Bolivia				6410	
Ecuador				6380	
Sudan				6270	
Estonia	Yes	Unknown	Unknown	6250	
Ethiopia				6130	
Lebanon				5940	
Haiti				5860	
Uganda				5850	
Chad				5840	
Luxembourg	Yes	Unknown	Unknown	5790	Toth, 2007
Mongolia				5770	
Tunisia				5660	
Cyprus	Yes	Unknown	Unknown	5650	
Cambodia				5640	
Trinidad and Tobago				5600	
Kazakhstan				5590	
Zimbabwe				5560	
Guatemala				5550	
Afghanistan				5540	
Senegal				5490	
Lithuania				5440	
Samoa				5360	
Algeria				5230	

Continuation Table II.

Country	Regulatory Framework	Scientific Framework	Technologies Employed[1]	Search Result	References
Saint Vincent and the Grenadines				5220	
Laos				5190	
Oman				5180	
Syria				5180	
Serbia				5120	
Mali				5100	
Papua New Guinea				5080	
Malta	Yes	Unknown	Unknown	5050	
United Arab Emirates	Unknown	Yes	Unknown	5050	El-Sammak 2001
Uruguay				5030	
Mozambique				4870	
Namibia				4870	
Bahamas				4840	
Bosnia and Herzegovina				4840	
Cameroon				4800	
Marshall Islands				4780	
Zambia				4750	
Madagascar				4740	
Latvia	Yes	Unknown	Unknown	4670	
Nicaragua				4650	
Central African Republic				4560	
Fiji				4560	
El Salvador				4530	
Burma (Myanmar)				4460	
Congo (RoC)				4380	
Honduras				4380	
Albania	Unknown	Yes	Unknown	4370	Celo 2004
Armenia				4350	
Botswana				4320	
Angola	Unknown	Yes	Unknown	4300	Africa Report, 2008
Dominican Republic				4260	
Guyana				4190	
Malawi				4120	
Libya				4100	
Belarus				4070	
Azerbaijan				4040	
Grenada				4040	
Uzbekistan				4040	
Belize				4000	
Paraguay				3990	
Barbados				3980	
Mauritius				3950	
Macedonia				3890	
Palestine				3820	
Bahrain				3780	
Montenegro				3780	
Solomon Islands				3730	
Benin				3710	

Continuation Table II.

Country	Regulatory Framework	Scientific Framework	Technologies Employed[1]	Search Result	References
Qatar				3680	
Saint Lucia				3670	
Sierra Leone				3550	
Somalia				3550	
Gabon				3520	
Yemen				3520	
Liberia				3450	
Moldova				3370	
Rwanda				3360	
Cape Verde				3310	
Burkina Faso				3270	
Suriname				3270	
Saint Kitts and Nevis				3250	
Democratic Republic of the Congo				3200	
Seychelles	Yes	Unknown	Unknown	3190	National Assembly 1994
Liechtenstein				3110	
Tonga				3110	
Micronesia				3100	
San Marino				3050	
Bhutan				3030	
Antigua and Barbuda				2990	
Brunei				2980	
The Gambia				2970	
Mauritania				2940	
Equatorial Guinea				2870	
Swaziland				2830	
Maldives				2790	
Kyrgyzstan				2750	
Palau				2720	
Kosovo				2700	
Tajikistan				2660	
Côte d'Ivoire				2630	
Turkmenistan				2630	
Burundi				2620	
Eritrea				2570	
Vatican City				2540	
Dominica				2520	
Lesotho				2510	
Vanuatu				2430	
East Timor				2360	
São Tomé and Príncipe				2160	
Djibouti				2100	
Comoros				1990	
Guinea-Bissau				1930	
Kiribati				1890	
Tuvalu				1810	
Nauru				1630	
Andorra				1490	

[1]Abbreviation Definitions	
b	Bioremediation
et	Ex-Situ Remediation
it	In-Situ Remediation
d	Dredging
c	Capping
nr	Natural Resources
ss	Stabilization/Solidification
l	Lagooning
sp	Sediment Processing

CONCLUSIONS

It is safe to conclude that the current snapshot presented here will change, perhaps dramatically, over time. While this single set of results does not allow identification of a trend, it seems reasonable to speculate that the number of countries with regulatory frameworks for management of contaminated sediment will continue to expand as concerns about the risks of contaminated sediment and debate about the best approaches to remediation continue to mount.

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