Hindawi Publishing Corporation
International Journal of Oceanography
Volume 2016, Article ID 8097861, 10 pages
http://dx.doi.org/10.1155/2016/8097861

Research Article

Simulation of Sediment Discharges during an Outfall Dredging Operation

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Received 31 October 2015; Accepted 31 December 2015

Academic Editor: Heinrich Hühnerfuss

CORMIX-GTS simulations are carried out to study suspended muddy sediment plumes following the discharge of the spoils taken from the seabed during a marine outfall pipeline dredging operation. Single port discharges are considered at three different locations at 400 m, 800 m, and 1200 m from the shoreline with water depths ranging from 3.5 m to 10.5 m. For discharges in the shallow near-shore region at 400 m offshore, most of the dredge materials are deposited at the seabed and the simulated suspended sediment plumes are found to be carrying a concentration of less than 1 kg/m^3 of mainly fine silt and clay. For discharges in the deeper far-shore region at 1200 m offshore, the sediment plumes are more elongated and carrying a concentration of more than 3 kg/m^3. Iterative simulations are also conducted to analyse the inherent uncertainty in the input data by varying the ambient velocity and the port's horizontal angle of discharge.

1. Introduction

For coastal capital cities, the practical strategy of wastewater disposal through an effective marine outfall is an affordable, effective, and reliable solution that is simple to operate and with minimal health and environmental impacts [1]. Modern wastewater treatment plants build a sufficiently long outfall pipeline for continuous discharges of treated wastewaters into the open sea. Underwater seabed excavation is therefore needed to establish a channel for laying and burying a submerged outfall pipeline, where the unwanted dredged material is disposed of at sea. The bar channel's length could be more than 1 km offshore, and the diameter of the pipe to be buried in the channel could be as large as up to 1.5 m.

In the shallow near-shore region, less than 400 m from the shoreline, a mechanical dredger is usually used to remove the soil by scooping it with buckets from the seabed and placing it onto a waiting flat barge. Once the barge is full, it will transport the collected materials to a designated disposal site, where the dredged (suspended) sediment is discharged from the bottom of the barge. With the usage of two or more disposal barges, dredging operations can proceed continuously, only interrupted by changing barges or moving the dredger. However, since these mechanical dredgers are mounted on a large barge and are towed to the dredging site, they are not well suited for areas of rough seas. Therefore, in the far offshore region more than 400 m away from the shore, the side-casting disposal of dredged sediment is adopted, where the dredged materials taken from the seabed are directly discharged overboard to the side through an elevated discharge pipe into the sea surface.

The main environmental concerns for the underwater channel excavation and discharging dredged materials in coastal waters are associated with suspended sediments and increases in turbidity, which may result in an extended reduction in light penetration into the water column [2–7]. In general, however, these effects are short term and confined to the near field. Turbidity represents a complex composite of several variables that collectively influence the transparency of water. Frequently, as it may also contain plankton and microorganisms, it is poorly correlated with measurements of suspended solids [8]. The environmental effects of dredging are mainly dependent on where the spoil is deposited, and since temporarily suspended sediment plumes are mixed and dispersed by tidal currents, one of the purposes of the discharges is to make sure that dredged sediments are not deposited back to the bar channel. The particle size of sediments is of importance in understanding their likely impact in coastal waters. For example, sand particles settle quickly (the fall velocity of sand is about 31 mm/s compared to that of fine silt being 0.026 mm/s) and are unlikely to move from the disposal site unless subject to extremely strong currents. Muddy sediment (up to fine silt size) in turbidity plumes is expected to settle more slowly, and this dredged particle could remain in suspension and be carried for more than 20 km downstream of the discharge point [2, 4, 6, 7].

The aim of this paper is to study the dispersion of dredged plume discharges during the seabed dredging work for laying and burying sea outfall pipelines. CORMIX-GTS (v9.0) simulations are carried out to assess the impact of dredging-induced turbidity plumes on the marine environment. The first simulation sets correspond to side-casting (near-shore) discharges at 400 m offshore with a shallow water depth of 3.5 m, the second sets correspond to (midshore) discharges at 800 m offshore with a water depth of 7.0 m, and the third sets correspond to (far-shore) discharges at 1200 m with a deeper water depth of 10.5 m, where the dredged sediments are released through a single port at 1 m above the sea surface.

2. CORMIX Mixing Zone Model

The CORMIX modelling package (http://www.cormix.info/) is a software system for the analysis, prediction, and design of marine outfall mixing zones resulting from a continuous point discharge of effluents into open coastal waters [9]. It employs an easy-to-use rule-based expert system to screen input data and check for consistency and selects the appropriate hydrodynamic model to simulate the physical mixing processes likely to be present for many complex flow patterns within a given discharge-environment interaction (e.g., see Figure 1). Efficient computational algorithms provide simulation results in seconds for mixing zone problems with spatial scales of meters to kilometers. Extensive comparison with available field and laboratory data has shown that the CORMIX system predictions on plume concentrations (with associated plume geometries) are reliable for the majority of cases [10, 11].

The hydrodynamic flow classification schemes in the CORMIX system are developed based on dimensional analysis arguments as the detailed methods for modelling the dynamics of effluent discharges in complex physical situations are not available. Using the user input parameters, CORMIX classifies the flow class of the effluent discharge in the receiving water body based on the relative magnitudes of length scales (e.g., see Figure 1). These length scales, which measure the influence of each potential mixing process due to momentum flux and buoyancy of the discharge in relation to boundary interactions, are then used to predict steady-state mixing zone characteristics and plume dynamics such as free jets, shoreline-attached jets, wall jets, and upstream intruding plumes [9, 10]. The model system has the ability to capture the key stages of effluent plume evolution: (i) in the near field region, where jet/plume dynamics are dominated by the momentum of the discharge; (ii) in the buoyant spreading region, where the buoyancy of the effluent stream is dynamically important; and (iii) in the ambient spreading region, where full vertical mixing has occurred and the effluent plume is controlled by the ambient flow.

CORMIX-GTS has advanced tools for suspended sediment (dredge sediments option) that extends the capability of CORMIX to simulate the initial mixing and dispersion of dredge sediment discharge, which includes side-casting surface discharge of sediments [11], and the (hydrodynamic module) DHYDRO simulates dense suspended sediment discharges (submerged, surface, and above surface) from a single port. CORMIX-GTS was developed in part through cooperation with the US EPA, the US Army Corps of Engineers, and the US Bureau of Reclamation [12].

The model includes the Stokes effect of particle settling on plume behaviour, with emphasis on the resulting plume density current, and accounts for the settling of five particle size classes, when using the default dredge sediments option [9, 11]: chunks: large, nonsuspended solids and stones which will separate out immediately from the plume; sand: suspended particles with settling velocity 0.031 m/s; coarse silt: suspended particles with settling velocity 0.42×10^{-3} m/s; fine silt: suspended particles with settling velocity 0.26×10^{-4} m/s; and clay: suspended particles with settling velocity 0.65×10^{-6} m/s. For the shallow water depth of 3.5 m, the settling time for sand particles is about 2 minutes, for coarse silt about 2.3 hours, for fine silt about 1.6 days, and for clay particle more than 62 days.

3. Near-Shore Discharges at 400 m from the Shoreline

The input data for the (above surface) side-casting discharge of dredge sediments at a distance of 400 m from the shoreline are summarized in Table 1, where the dredged sediments with a (total) concentration of 200 kg/m^3 (set as 100%) are discharged overboard of the barge through an elevated (45° inclined) pipe at 1 m above the sea surface to an unbounded, uniform sloping bed coastal environment. According to the particle sizes, this initial dredge sediment discharge consists of sand 20 kg/m^3, coarse silt 40 kg/m^3, fine silt 60 kg/m^3, and clay 80 kg/m^3. For the impact assessment study of effluent discharges in the marine environment, the region of interests would be a circular distance up to 500 m around the outfall discharge, and thus the CORMIX-GTS base simulation will be terminated at 1000 m downstream (in the ambient flow direction, x-axis). The ambient density is calculated at a temperature of 30°C (with a seawater salinity of 38 ppt), and similarly, using total sediment concentration of 200 kg/m^3, CORMIX calculates the effluent sediment density to be 1146.7 kg/m^3. Since the effluent density is greater than the surrounding water density 1023.98 kg/m^3, the resuspended

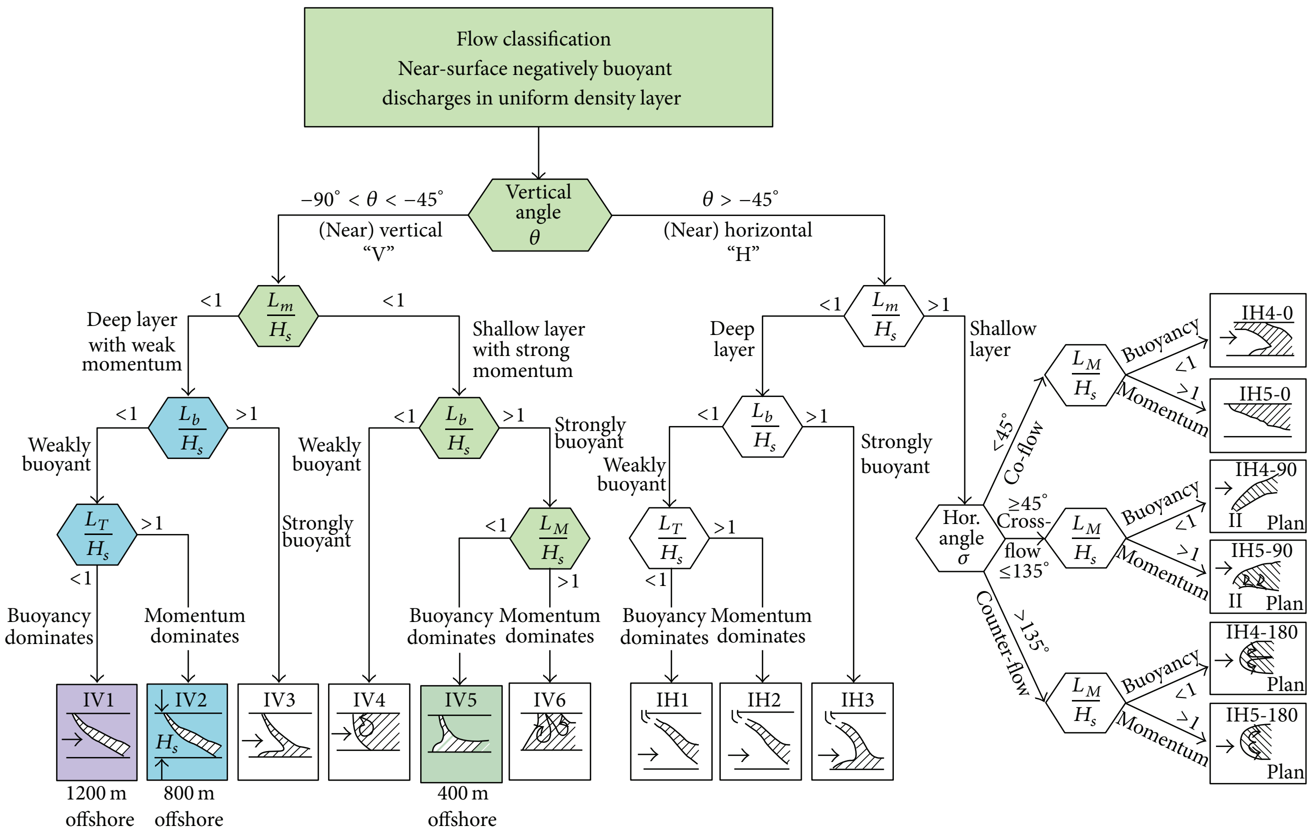


FIGURE 1: CORMIX flow classification for single port discharge in a uniform density layer [9].

TABLE 1: Input data for the CORMIX-GTS base simulations of dredge sediment discharges.

Parameter	Side-casting discharge			Unit
		Ambient (unbounded environment)		
Velocity of the currents	0.3	0.5	0.6	m/s
Depth at discharge	3.5	7.0	10.5	m
Wind speed		3		m/s
(Single) bottom slope		0.5		°
Temperature		30		°C
Salinity		38		ppt
(Uniform) density		1023.98		kg/m^3
		Discharge (single port)		
Distance to nearest (right) bank	400	800	1200	m
Port diameter		0.5		m
Port height above the surface		1.0		m
Theta = vertical angle		45		°
Sigma = horizontal angle		90		°
Sediment = effluent flow rate		0.5		m^3/s
Effluent density		1146.7		kg/m^3
		Effluent (dredge sediment)		
Concentration		200 (= 100%)		kg/m^3
Chunks (nonsuspended sediments > 2 mm)		0		%
Sand (suspended sediments 0.062–2 mm)		10		%
Coarse silt (suspended sediments 0.016–0.062 mm)		20		%
Fine silt (suspended sediments 0.004–0.016 mm)		30		%
Clay (suspended sediments < 0.004 mm)		40		%

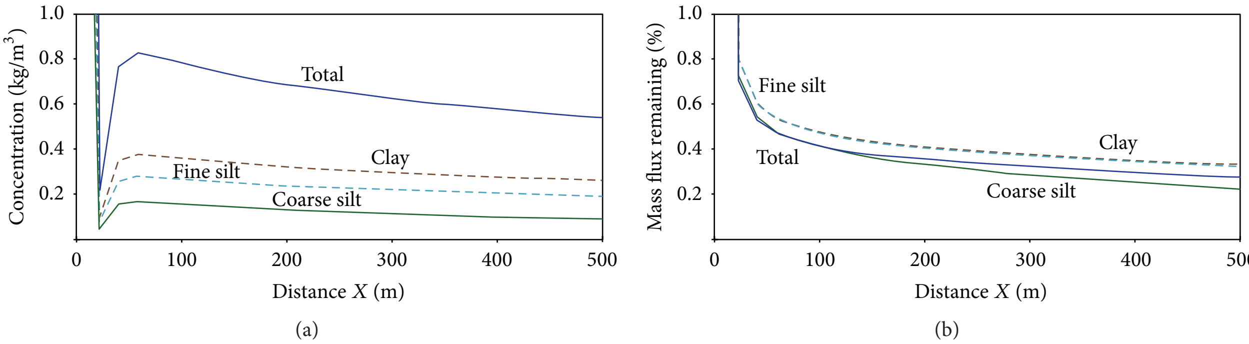


Figure 2: CORMIX-GTS simulations of near-shore discharges of dredge sediment at 400 m from the shoreline: (a) suspended sediment distribution (in the ambient flow direction) up to 500 m downstream from the discharge position and (b) sediment concentration (in %) remaining in the suspension.

sediment (dense) plume is negatively buoyant and eventually sinks at the seabed.

To account for any lateral displacement from the discharge pipe to the point of entry at the water surface, CORMIX recomputed an additional distance travelled by the effluent discharge as 1.21 m with a vertical angle at entry -69°. The new discharge position is thus set at 401.21 m from the shoreline. CORMIX classifies this kind of sediment flow as the flow class IV5 [9], a (surface) negatively buoyant flow in a (shallow) uniform density layer corresponding to the water depth 3.51 m. This discharge configuration is claimed to be hydrodynamically stable, and as the initial jet-like discharge is weakly deflected by the ambient current into the flow direction, but due to the strong discharge buoyancy, the slightly bent over plume rapidly sinks to the sloping bed and impinges on the seabed within 21.84 m downstream (below the entry point). Impingement is a complex three-dimensional process, with more or less radial spreading, where the sediment accumulation of bottom deposit is formed [11]. Thereafter, as the suspended muddy plume loses its buoyancy by particle deposition at seabed, the plume continues to spread laterally as a bottom density current at the seabed while it is being advected by the ambient current, resulting in thinning of the plume and increased nonlinear lateral spreading.

After the sediment deposition at seabed, the muddy plume starts to resuspend with an initial mass flux remaining of 0.72% carrying a total suspended concentration of 0.22 kg/m^3, which mainly consists of coarse silt 0.05 kg/m^3, fine silt 0.07 kg/m^3, and clay 0.10 kg/m^3. As shown in Figure 2, the total suspended concentration is increased in a short distance, reaches a maximum value of 0.83 kg/m^3, and then disperses downstream. The dominant particle sizes in the suspended plume are clay, fine silt, and coarse silt, as represented in CORMIX-GTS by the sediment mass flux remaining, and, at the end of simulation (1000 m downstream), there is clay with more than 0.27%, fine silt with 0.26%, and coarse silt with 0.13%.

The (total) concentration contours of the simulated suspended sediment plume are shown in Figure 3 at 100 m intervals. The total concentration is steadily reducing (after loss of suspended particles by settling) from 0.79 kg/m^3 at 100 m to 0.54 kg/m^3 at 500 m downstream, and eventually it reaches a value of 0.42 kg/m^3 at 1000 m downstream (end of simulation). The lateral spreading of the contour centerline at 100 m is 61 m, and it is increased to 174 m at 500 m downstream.

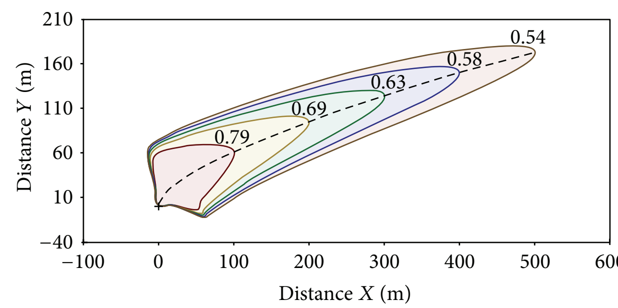


Figure 3: Contours of the suspended sediment concentration (in kg/m^3) as simulated by CORMIX-GTS following discharge at 400 m offshore.

A sensitivity analysis is carried out to address CORMIX model performance due to inherent uncertainty in the input data [13]. First, to investigate the uncertainty in sea conditions, iterative simulations were carried out by varying the ambient velocity, while holding the other input parameters the same as the base simulation given in Table 1. The CORMIX-GTS simulation results for increasing the ambient velocity values from 0.2 to 0.7 m/s are presented in Table 2, where there is flow class change from IV5 to IV4 for velocities larger than 0.6 m/s. As the velocity values are reduced from 0.55 m/s, the size of bed deposition region increases and there are less particles resuspended. The flow class IV4 is classified as hydrodynamically unstable in CORMIX system [9, 11], as the momentum flux dominates and there is weak buoyancy of the discharge. The flow becomes unstable after impingement and forms a recirculating region immediately downstream over the full (shallow) water depth. The simulation results for flow class IV4 show overall higher sediment concentrations than that of class IV5.

The end of the (total) sediment concentration sharp drop (due to the initial seabed impingement) as shown in Figure 2

Table 2: Summary of CORMIX-GTS iterative simulations results on varying the ambient velocity for discharges at 400 m offshore.

Ambient velocity (m/s)	Flow class	Initial resuspension			100 m		500 m		1000 m	
		At (m)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)
0.2	IV5	24.95	0.06	0.03	0.37	0.18	0.28	0.14	0.23	0.13
0.25	IV5	23.03	0.13	0.06	0.56	0.26	0.41	0.20	0.33	0.17
0.3	IV5	21.84	0.22	0.10	0.79	0.36	0.54	0.26	0.42	0.21
0.35	IV5	21.02	0.36	0.16	1.07	0.49	0.68	0.33	0.50	0.25
0.4	IV5	20.46	0.61	0.27	1.44	0.65	0.82	0.39	0.58	0.29
0.45	IV5	19.97	1.06	0.46	1.94	0.87	0.98	0.47	0.67	0.33
0.5	IV5	19.54	2.01	0.85	2.69	1.20	1.24	0.59	0.81	0.41
0.55	IV5	19.58	3.30	1.38	4.25	1.91	1.85	0.89	1.18	0.61
0.6	IV4	22.91	14.11	6.06	12.68	5.79	5.35	2.76	3.34	1.90
0.65	IV4	23.30	14.83	6.36	13.26	6.06	5.59	2.88	3.49	1.97
0.7	IV4	23.60	15.40	6.59	13.82	6.31	5.83	3.00	3.64	2.05

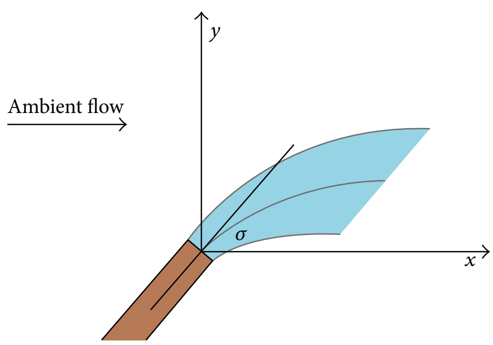


Figure 4: Diagram of the horizontal angle of discharge.

is referred to as the initial resuspension of sediment (in Table 2), and the subsequent suspended sediment concentrations are also reported at 100 m and 500 m downstream and finally at the end of CORMIX-GTS simulation at 1000 m downstream.

Next, the iterative CORMIX-GTS simulations were carried out to investigate the uncertainty in single port position by varying the horizontal angle of discharge σ from 0 to 135°, while holding the other input parameters the same as the base simulation given in Table 1 (and CORMIX system reports unstable configuration for angles bigger than 135°) [9]. As sketched in Figure 4, the port's horizontal angle of discharge is defined as the angle measured counterclockwise from the direction of ambient velocity (x-axis) to the plan projection of the port (centerline), and thus, a coflow discharge (in the ambient flow direction) refers to the port position when $\sigma = 0°$, a cross-flow discharge (in the direction perpendicular to the ambient flow) when $\sigma = 90°$, and a counterflow discharge when $\sigma = 180°$. Ideally, a counterflow discharge in the opposite direction of the ambient current velocity should be avoided.

The CORMIX-GTS simulation results for increasing the horizontal angle of discharge values from 0 to 135° are presented in Table 3, where there are no changes in the flow class IV5 reported. For this shallow water depth, CORMIX extends the specification of the counterflow discharges from $\sigma = 120°$, and thus the CORMIX (steady-state) results for both $\sigma = 120°$ and $\sigma = 135°$ are unrealistic and should be ignored. Similarly, CORMIX also specifies the coflow discharges for $\sigma \leq 30°$, and the prediction is that muddy suspended plumes are more elongated (in the ambient flow direction) with less dispersion. It is suggested that CORMIX preferred horizontal angle of discharge is between 30° and 105°.

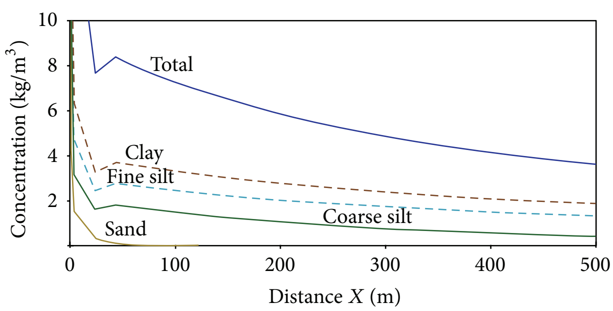
4. Midshore Discharges at 800 m from the Shoreline

The input data for the CORMIX-GTS base simulation for the side-casting dredge sediment discharge through an elevated (45° inclined) pipe at 1 m above the sea surface at a distance of 800 m from the shoreline are summarized in Table 1. Similar to the previous discharge of sediment at 400 m offshore, CORMIX recomputed the discharge conditions at entry point at the water surface to account for any lateral displacement and sets a new discharge position at 801.21 m from the shoreline with a vertical discharge angle −69°. The sediment flow is classified as the flow class IV2, a (surface) negatively buoyant flow in a (deep) uniform density layer corresponding to the water depth 7.01 m [9]. The initial jet-like discharge in weak cross-flow is deflected by the ambient current and slowly sinks to the sloping bed. Deposition of sediments is occurring on the seabed within 23.79 m downstream (below the entry point), and, thereafter, as the suspended plume loses its buoyancy by particle settling, the muddy plume continues to spread laterally as a bottom density current at the seabed while it is being advected by the ambient current.

After sedimentation at the seabed (mainly due to the initial mass of larger sediment particles settling), the plume starts to resuspend with an initial mass flux remaining of 4.87% carrying a total suspended concentration of 7.64 kg/m^3, which mainly consists of sand 0.33 kg/m^3, coarse silt 1.61 kg/m^3, fine silt 2.44 kg/m^3, and clay 3.26 kg/m^3. As

Table 3: Summary of CORMIX-GTS iterative simulations results on varying the horizontal angle of discharge for discharges at 400 m offshore.

Sigma (degrees)	Flow class	Initial resuspension			100 m		500 m		1000 m	
		at (m)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)
0	IV5	22.12	3.76	1.58	4.12	1.86	1.70	0.84	1.07	0.58
15	IV5	21.91	3.61	1.52	4.11	1.86	1.71	0.85	1.07	0.58
30	IV5	21.27	3.46	1.45	4.13	1.86	1.73	0.86	1.09	0.59
45	IV5	30.99	0.23	0.11	0.67	0.31	0.42	0.20	0.32	0.16
60	IV5	29.24	0.23	0.10	0.70	0.31	0.45	0.21	0.34	0.17
75	IV5	26.25	0.22	0.10	0.72	0.33	0.49	0.23	0.37	0.19
90	IV5	21.84	0.22	0.10	0.79	0.36	0.54	0.26	0.42	0.21
105	IV5	15.94	0.22	0.10	0.87	0.41	0.63	0.31	0.50	0.26
120	IV5	9.40	0.21	0.09	0.74	0.34	0.35	0.17	0.21	0.11
135	IV5	8.98	0.21	0.09	0.70	0.32	0.37	0.18	0.23	0.12



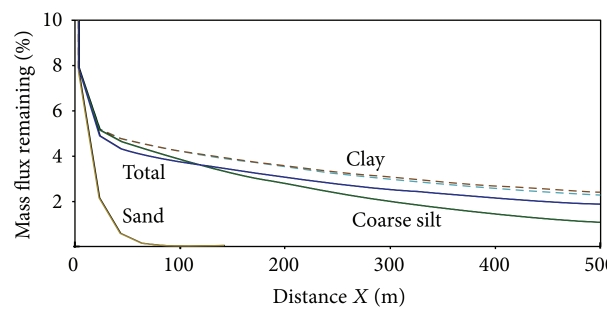


Figure 5: CORMIX-GTS simulations of midshore discharges of dredge sediment at 800 m from the shoreline: (a) suspended sediment distribution (in the ambient flow direction) up to 500 m downstream from the discharge position and (b) sediment concentration (in %) remaining in suspension.

shown in Figure 5, the total suspended concentration jumped immediately to reach a maximum value of 8.40 kg/m^3 and then disperses downstream. Within 500 m downstream, the dominant particle sizes in the suspended plume are clay, fine silt, and coarse silt, as represented in CORMIX-GTS by the sediment mass flux remaining. The first particle size to settle out completely from the plume is sand within 83 m downstream, and, at the end of simulation (1000 m downstream), there is clay with more than 1.65%, fine silt with 1.48%, and coarse silt with 0.27%.

The (total) concentration contours of the simulated suspended sediment plume are shown in Figure 6 at 100 m intervals. The total concentration is steadily reducing (after loss of suspended particles by settling) from 7.21 kg/m^3 at 100 m downstream to 3.61 kg/m^3 at 500 m and eventually reaches a value of 2.29 kg/m^3 at 1000 m downstream (end of simulation). The plume is elongated in the ambient flow direction with the lateral spread of contour centerline at 500 m to be slightly over 40 m.

The CORMIX-GTS iterative simulation results of increasing the ambient velocity from 0.3 to 0.7 m/s are presented in Table 4, where there is a flow class change from IV2 to IV3 and IV5 for velocities 0.45 m/s and smaller than 0.4 m/s, respectively. After the impingement, and due to a strong buoyancy, the flow class IV3 spreads at the seabed over some distance upstream against the ambient flow up to the intrusion length of 5.21 m. For weaker ambient currents, the upstream intrusion length of the flow class IV5 is getting longer, and it reaches 10.30 m for the ambient velocity 0.3 m/s. The simulation results show overall higher sediment concentrations than that of flow class IV2 with stronger currents greater than 0.5 m/s.

The iterative simulation results on varying the horizontal angle of discharge from 0 to 135° are presented in Table 5, where there are no changes in the flow class IV2 reported. It is found that, similar to the previous near-shore discharges, the CORMIX preferred horizontal angle of discharge is between 30° and 90° and will produce a smaller suspended sediment concentration.

5. Far-Shore Discharges at 1200 m from the Shoreline

Input data for the side-casting discharge of dredge sediment through an elevated (45° inclined) pipe at 1 m above the sea surface at a distance of 1200 m from the shoreline are summarized in Table 1. Again, CORMIX-GTS recomputed

Table 4: Summary of CORMIX-GTS iterative simulations results on varying the ambient velocity for discharges at 800 m offshore.

Ambient velocity (m/s)	Flow class	Initial resuspension			100 m		500 m		1000 m	
		At (m)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)
0.3	IV5	26.12	11.89	5.42	9.13	4.45	4.85	2.92	3.36	2.21
0.35	IV5	25.47	11.53	5.21	9.38	4.49	4.96	2.92	3.37	2.17
0.4	IV5	25.00	11.03	4.95	9.20	4.33	5.02	2.89	3.36	2.12
0.45	IV3	24.80	10.47	4.66	8.81	4.10	5.01	2.81	3.31	2.05
0.5	IV2	23.79	7.64	3.26	7.21	3.28	3.61	1.87	2.29	1.30
0.55	IV2	24.37	7.56	3.21	7.06	3.20	3.85	1.98	2.45	1.39
0.6	IV2	24.94	7.49	3.17	6.81	3.09	4.06	2.07	2.60	1.46
0.65	IV2	25.53	7.02	2.95	6.35	2.87	4.18	2.11	2.74	1.53
0.7	IV2	26.21	6.58	2.75	5.81	2.62	4.18	2.08	2.86	1.58
0.75	IV2	26.88	6.20	2.59	5.29	2.38	4.04	1.99	2.94	1.61
0.8	IV2	27.69	5.90	2.45	4.84	2.17	3.84	1.87	2.96	1.60

Table 5: Summary of CORMIX-GTS iterative simulations results on varying the horizontal angle of discharge for discharges at 800 m offshore.

Sigma (degrees)	Flow class	Initial resuspension			100 m		500 m		1000 m	
		At (m)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)
0	IV2	26.15	9.10	3.88	7.05	3.21	3.34	1.71	2.10	1.19
15	IV2	26.04	8.58	3.65	6.93	3.15	3.34	1.71	2.11	1.19
30	IV2	25.83	8.16	3.47	6.84	3.11	3.36	1.72	2.12	1.20
45	IV2	25.49	7.84	3.34	6.81	3.09	3.39	1.74	2.14	1.21
60	IV2	25.03	7.65	3.26	6.85	3.12	3.44	1.77	2.18	1.23
75	IV2	24.46	7.58	3.23	6.48	3.18	3.51	1.81	2.23	1.26
90	IV2	23.79	7.64	3.26	7.21	3.28	3.61	1.87	2.29	1.30
105	IV2	23.12	7.82	3.34	7.51	3.42	3.72	1.93	2.36	1.35
120	IV2	22.56	8.15	3.49	7.82	3.56	3.81	1.99	2.41	1.39
135	IV2	22.15	8.71	3.74	8.14	3.71	3.87	2.02	2.44	1.41

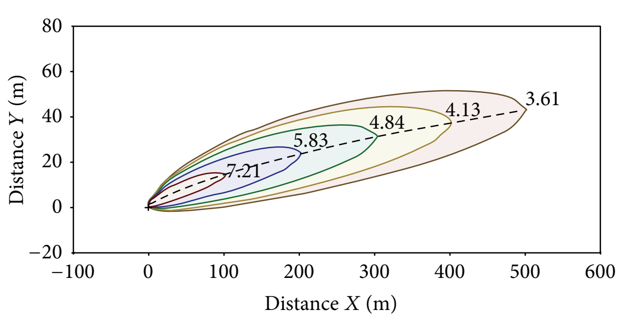


Figure 6: Contours of the suspended sediment concentration (in kg/m^3) as simulated by CORMIX-GTS following discharge at 800 m offshore.

the discharge conditions to account for any lateral displacement and set a new discharge position of 1201.21 m from the shoreline with a vertical discharge angle −69° at entry point at the water surface. The sediment flow is classified as the flow class IV1, a (surface) negatively buoyant flow in a (deep) uniform density layer corresponding to the water depth 10.51 m [4]. The initial jet/plume in strong cross-flow is strongly deflected by the ambient current and rapidly falls toward the sloping seabed within 30.38 m downstream, and the plume stays at the seabed due to its negative buoyancy with loss of suspended particles by sedimentation. Thereafter, the plume continues to travel downslope as a bottom density current at the seabed while it is being advected by the ambient current.

As shown in Figure 7, the suspended sediment plume disperses downstream with an initial mass flux remaining of 2.13% carrying a total suspended concentration of 4.09 kg/m^3, which mainly consists of sand 0.27 kg/m^3, coarse silt 0.84 kg/m^3, fine silt 1.27 kg/m^3, and clay 1.7 kg/m^3. Similar to the previous sediment discharge at 800 m offshore, the dominant particle sizes in the muddy suspended plume are, as represented in CORMIX-GTS by the sediment mass flux remaining, clay, fine silt, and coarse silt. The first particle size to settle out completely from the plume is sand within

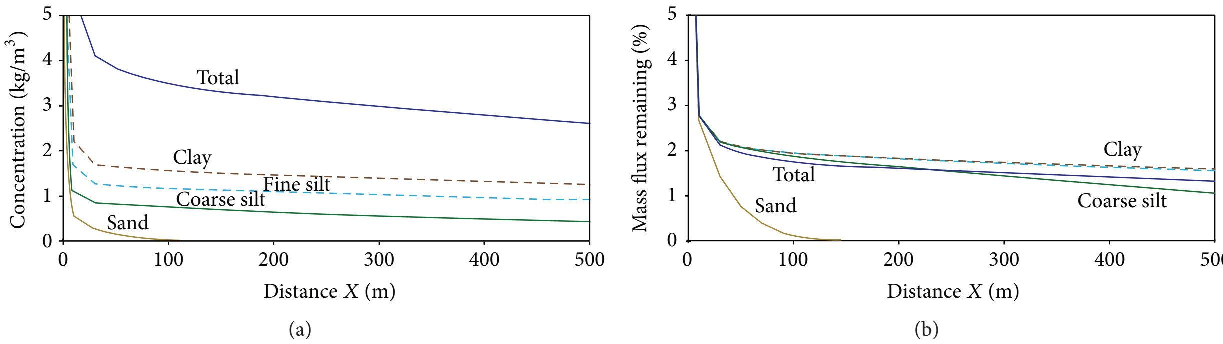


FIGURE 7: CORMIX-GTS simulations of far-shore discharges of dredge sediment at 1200 m from the shoreline: (a) suspended sediment distribution (in the ambient flow direction) up to 500 m downstream from the discharge position and (b) sediment concentration (in %) remaining in the suspension.

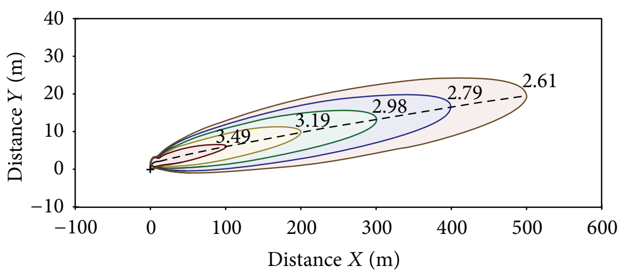


FIGURE 8: Contours of the suspended sediment concentration (in kg/m^3) as simulated by CORMIX-GTS following discharge at 1200 m offshore.

150 m downstream and, at the end of simulation (1000 m downstream), there is clay with more than 1.25%, fine silt with 1.17%, and coarse silt with 0.44%.

The (total) concentration contours of the simulated suspended sediment plume are shown in Figure 8 at 100 m intervals. The total concentration is steadily reducing (after loss of suspended particles by settling) from 3.49 kg/m^3 at 100 m to 2.61 kg/m^3 at 500 m downstream and eventually reaches a value of 1.86 kg/m^3 at 1000 m downstream (end of simulation). The plume is more elongated in the flow direction with the lateral spread of the contour centerline at 500 m at slightly less than 20 m, that is, half the width of the previous midshore discharges.

The CORMIX-GTS iterative simulation results of increasing the ambient velocity from 0.4 to 0.9 m/s are presented in Table 6, where there is a flow class change from IV1 to IV3 for velocities smaller than 0.4 m/s. Due to strong buoyancy and weaker current, and, after the impingement, the flow class IV3 spreads at the seabed over some distance upstream against the ambient flow up to the intrusion length of 7.01 m. As the current is increased from 0.45 m/s, the size of the bed deposition region increases and there are less sediments resuspended.

Next, the iterative CORMIX-GTS simulations were carried out by varying the position of discharge from 0 to 135°. The results are presented in Table 7, where there are no changes in the flow class IV1 reported. Again, it is clear that, for the near coflow discharges for $\sigma \leq 30^\circ$, CORMIX predictions are only slightly different, and, however, the near counterflow discharges for $\sigma \geq 105^\circ$ should be avoided.

6. Conclusion

CORMIX-GTS simulations were run for three scenarios of side-casting (above surface) discharges of seabed dredge sediments during an outfall dredging operation at 400 m, 800 m, and 1200 m from the shoreline, where the initial dredged seabed spoil consists of sand 20 kg/m^3, coarse silt 40 kg/m^3, fine silt 60 kg/m^3, and clay 80 kg/m^3. The dredging-induced turbidity plumes with a concentration of more than 0.03 are visible from the surface.

CORMIX-GTS simulation results for discharges in the near shore (at 400 m from the shoreline) with a shallow water depth of 3.5 m show that most of the sediments are immediately deposited at the seabed due to the initial momentum and buoyancy of discharge, and the muddy turbidity plumes with a concentration of less than 1 kg/m^3 of mainly coarse silt, fine silt, and clay are remained in suspension for large distances more than 500 m downstream. For discharges in the far shore (at 1200 m from the shoreline) with a deeper water depth of 10.5 m, the results show that bottom sedimentation is formed by sediments settling out, and the suspended sediment plumes are more elongated (in the ambient flow direction) and carrying a concentration of more than 3 kg/m^3 of coarse silt, fine silt, and clay. Therefore, if a suitable disposal site can be chosen from the regional bathymetry of the coastline to absorb the accumulation of bottom deposit, then discharges in the near shore are the preferred and best option.

CORMIX-GTS simulations also predict that, for the near coflow discharges with the horizontal angle of discharge $\sigma \leq 30^\circ$, the muddy suspended sediment plumes are more elongated with less dispersion. The near counterflow discharges for $\sigma \geq 105^\circ$ (i.e., in the opposite direction of the ambient velocity) should be avoided. It is suggested that the CORMIX preferred horizontal angle of discharge is between 30° and 105°.

Table 6: Summary of CORMIX-GTS iterative simulations results on varying the ambient velocity for discharges at 1200 m offshore.

Ambient velocity (m/s)	Flow class	Initial resuspension			100 m		500 m		1000 m	
		At (m)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)
0.4	IV3	28.06	5.81	2.57	5.00	2.29	3.20	1.71	2.13	1.26
0.45	IV1	26.99	4.96	2.09	4.35	1.96	2.42	1.21	1.55	0.85
0.5	IV1	27.97	4.74	1.99	4.11	1.85	2.56	1.27	1.67	0.91
0.55	IV1	29.15	4.49	1.88	3.83	1.72	2.64	1.30	1.78	0.96
0.6	IV1	30.38	4.09	1.70	3.49	1.55	2.61	1.26	1.86	0.99
0.65	IV1	31.65	3.77	1.56	3.11	1.38	2.44	1.17	1.89	0.99
0.7	IV1	33.04	3.48	1.44	2.80	1.23	2.26	1.07	1.85	0.96
0.75	IV1	34.48	3.19	1.31	2.55	1.12	2.08	0.98	1.78	0.90
0.8	IV1	35.95	2.94	1.21	2.36	1.03	1.93	0.90	1.68	0.84
0.85	IV1	37.60	2.73	1.12	2.23	0.97	1.80	0.83	1.59	0.78
0.9	IV1	39.25	2.55	1.04	2.10	0.91	1.69	0.78	1.50	0.73

Table 7: Summary of CORMIX-GTS iterative simulations results on varying the horizontal angle of discharge for discharges at 1200 m offshore.

Sigma (degrees)	Flow class	Initial resuspension			100 m		500 m		1000 m	
		At (m)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)	Total (kg/m^3)	Clay (kg/m^3)
0	IV1	28.06	3.97	1.65	3.31	1.48	2.47	1.19	1.78	0.94
15	IV1	26.99	3.94	1.63	3.28	1.45	2.45	1.18	1.77	0.94
30	IV1	27.97	3.91	1.62	3.24	1.44	2.44	1.18	1.77	0.94
45	IV1	29.15	3.88	1.61	3.24	1.44	2.44	1.18	1.78	0.94
60	IV1	30.38	3.89	1.61	3.28	1.46	2.47	1.19	1.80	0.95
75	IV1	31.65	3.96	1.64	3.36	1.50	2.52	1.22	1.82	0.97
90	IV1	33.04	4.09	1.70	3.49	1.55	2.61	1.26	1.86	0.99
105	IV1	34.48	4.27	1.78	3.67	1.64	2.69	1.31	1.91	1.02
120	IV1	35.95	4.49	1.87	3.86	1.73	2.79	1.36	1.95	1.05
135	IV1	37.60	4.75	1.98	4.06	1.81	2.88	1.41	1.98	1.07

One major inherent limitation in the CORMIX system is the representation of the coastal environment as a uniformly sloping cross section channel where the ambient velocity is assumed to be uniform. Another limitation is the flow classification based on hydrodynamic criteria using length scale analysis, where the subsequent simulation is carried out without detailed numerical analysis and computation. For example, as shown in Table 2, a slight variation in the input parameters may result in different flow classes. The steady-state sediment depositing density current on a sloping bed is used for the calculation, and the effect of ambient cross-flow is ignored.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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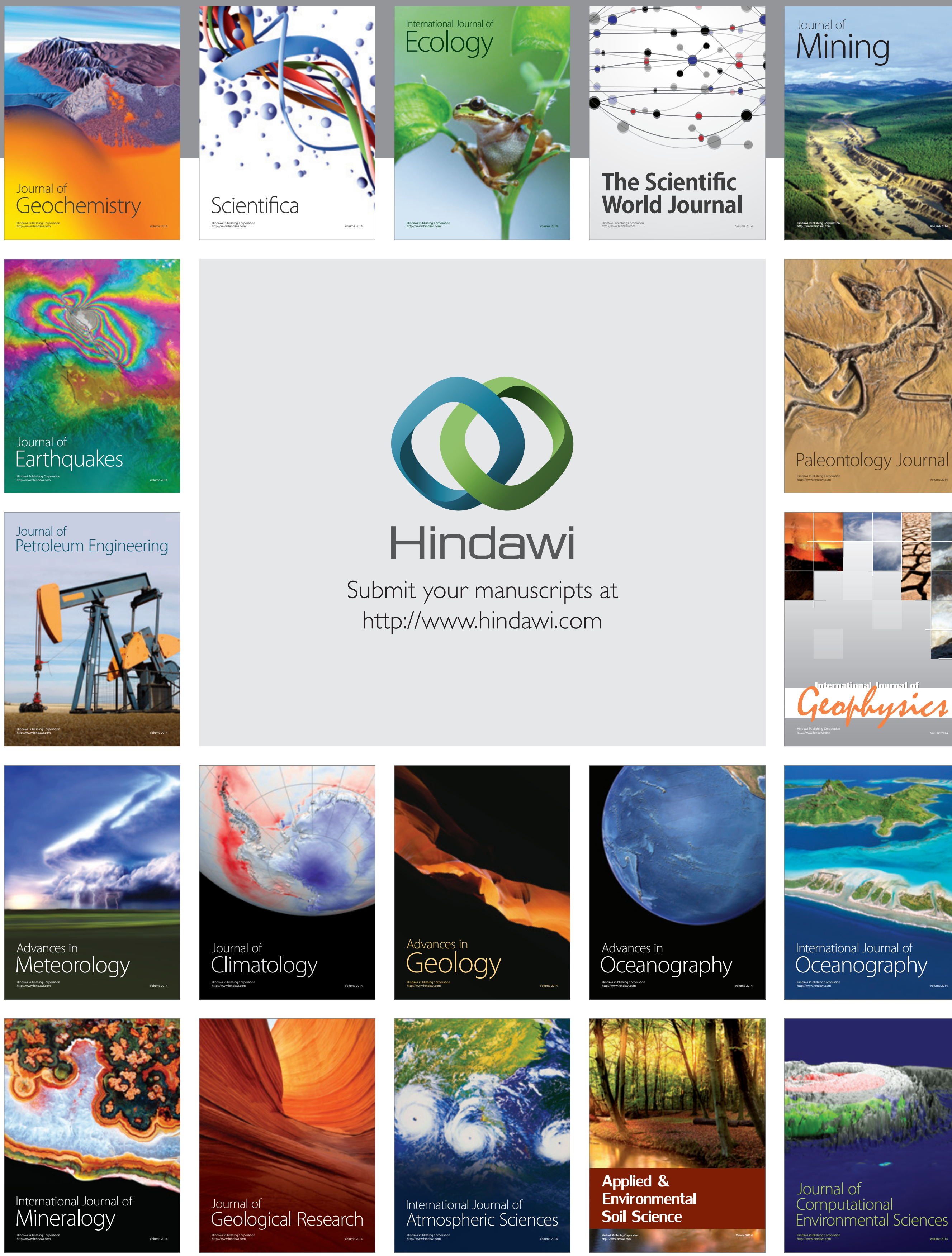
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