

Physical and Chemical Properties of Tsunami Deposits in the Northeast Area of Fukushima Prefecture after the Tohoku-Kanto Earthquake

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ABSTRACT: The damage done by deposits left by the tsunami triggered when the 11 March 2011 earthquake struck extended over a wide area in the coastal parts of the Tohoku district of Japan. The objectives of this study are to clarify physical and chemical properties of the tsunami deposits in Minamisoma City in northeast Fukushima Prefecture. From field research and measurements, two kinds of tsunami deposits, a sandy material and a muddy one, were observed. Muddy deposits, composed of small particles, were distributed in areas relatively far from shore. The particles in these deposits were light, and they contained high proportions of organic matter. Sandy deposits, on the other hand, had larger, much denser particles and were observed near the shoreline. The electrical conductivity of the muddy deposits at Kashima was very large. The Cl^- and SO_4^{2-} contents of the deposits were higher than those of paddy soils beneath. From an approximation of the shape of the area inundated by the tsunami and the bulk density and thickness of the deposits, we estimate that a dry mass of 193,000 Mg was deposited.

Keywords: Tsunami deposit, Particle size distribution, Particle density, Electric conductivity, Total amount of deposit

1. INTRODUCTION

The effects of the large tsunami, generated by an earthquake, which occurred on 11 March 2011, extended over a wide region of the Tohoku district of Japan. From a report by the Geospatial Information Authority of Japan (GIA) [1], the area inundated by the tsunami was estimated to be 560,000,000 m², which included many farming areas and farmlands. The Ministry of Agriculture, Forestry and Fisheries (MAFF) reported that 240,000,000 m² of farmland was damaged. It is generally presumed that the damaged farmland will be quickly reconstructed and restored.

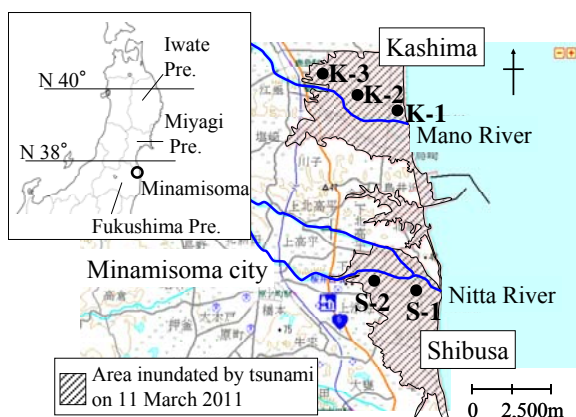


Fig. 1 Research Sites in this study

A tsunami's effects on farmland can be classified into three categories, (i) damage from salinization caused by infiltration of sea water into the soil, (ii) deterioration of the soil's physical, chemical, and biological properties due to deposition, and (iii) erosion of surface soil by the tsunami ([2]), with these effects sometimes being combined. Much damage was done by tsunami deposition, especially in coastal areas. To select methods of reconstructing farmland damaged by tsunami deposits, it is very important to have information about both the properties of material deposited and its amount. Also the properties of the soil under the deposits will change because deposition of earth and sand could compress the farmland's surface soil and chemicals eluted from the deposits could infiltrate into the soil.

The purpose of this study is to clarify the physical and chemical properties of tsunami deposits and to estimate the amount of them in northeast Fukushima Prefecture where there was serious damage done by the tsunami triggered by the Tohoku-Kanto earthquake.

2. SITES AND METHODS

2.1 Research Sites

Field research for this study was carried out in two areas, Kashima and Shibusa, in Minamisoma City, which is in the northeast part of Fukushima Prefecture (Fig. 1). The shoreline of these areas runs north and south, and the tsunami's waves were directed west. The tsunami ran 3,200 m inland in Kashima and 2,500 m in Shibusa. Three sites in Kashima (K-1, K-2, and K-3) and two sites in Shibusa (S-1 and S-2) were selected for measurements. These sites had been used as paddy fields before the tsunami event. At each site a sampling pit, 0.35 m deep at K-1 and S-1 and 0.25 m deep at the other sites, 0.50 m wide and 0.50 m long, was dug to investigate the profile of the deposits and the soil.

The field survey was conducted on 17 June 2011, 3 months after the tsunami event. The total amount of precipitation between the tsunami event and the survey was calculated to be 230 mm from AMeDAS data [3].

2.2 Sampling and Measurements

The thickness of the deposits was measured by observation of the profile of each sampling pit. Disturbed and undisturbed samples were taken from the profile. The undisturbed samples were taken using a 100 cm³ core sampler, 5.0 cm in diameter and 5.1 cm tall.

Particle size distribution was determined by the hydrometer method (for particles < 0.106 mm) and by sieving (for particles > 0.106 mm) after decomposing the organic

materials using hydrogen peroxide (following JIS A 1204). The water content and bulk density of the samples were measured by oven drying at 105 °C for 24 hours for both disturbed and undisturbed samples. The particle density of the disturbed samples was determined by the pycnometric method (JIS A 1202). Ignition loss, an indicator of the organic matter content, was calculated from the difference between the weight of oven dried samples and that of the samples heated to 800 °C for 3 hours in a muffle furnace. The saturated hydraulic conductivity of the undisturbed samples was determined by the falling-head method. A water extract was obtained from 4 g of the sample using 20 g of deionized water (following the 1:5 method) and the electric conductivity (EC) of this extract was measured. Chloride and sulfuric ion concentrations in the extracts were measured by Ion Chromatography (IC) (detector: CDD-10Avp, SHIMADZU) after passing them through a 0.22 µm filter. Particle size distribution, EC, and anion concentration were measured only on the samples from Kashima. Particle size distribution, EC, and anion concentration were replicated once, while measurements of other properties were replicated twice.

3 RESULTS AND DISCUSSION

3.1 Thickness of the Tsunami Deposits

In Kashima the thickness of the tsunami deposits decreased with distance from the shoreline similar to results reported in previous research [4]–[6] (Table 1). Muddy deposits were observed at K-3, which was farthest from shore. The presence of muddy surface deposit layers or muddy caps has also been reported previously [7]–[9]. The thickness of the deposits in coastal areas was greater because the large drop in the tsunami's velocity there promoted deposition of both earth and sand carried from the seabed. In Shibusa, on the other hand, at S-2, the deposits were thicker than at S-1 although S-2 is closer to the shore. Some reports show no clear relationship between the distance from the shoreline and the thickness of tsunami deposits [4], [10]. It is explained by changes in water flow velocity and direction due to

microtopography [5], [11], and deposition and erosion during the tsunami's outflow or in second and third inflows [12], [13]. When the tsunami runs up so fast and its water volume is so great, deposition may not occur in coastal areas because of its large transport ability. The thickness at S-1 was different from the average of K-1 and K-2 although S-1's distance from shore is about halfway between those of K-1 and K-2. The deposits seem to vary considerably in these two areas, even though they are only 3,000 m apart. The precise information of the thickness of the deposit is very important for the constructors who are going to remove the deposits. Further investigations are expected to clarify the spatial variability of the thickness.

3.2 Particle Size Distributions of the Deposits in Kashima

The particle size distributions of the deposits from the surface to a depth of 0.05 m at each site in Kashima are shown in Fig. 2(a). The deposits at K-3 had smaller particles ($D_{50} = 0.04$ mm) than those at K-1 ($D_{50} = 0.2$ mm) and K-2 ($D_{50} = 0.3$ mm). The sand fraction at K-3, in particular, was remarkably smaller. However, the particles in the deposits at K-2 were larger than at K-1, and no clear relationship was observed between distance from the shore and particle size. These results agree with previous reports [9], [14]. Moore et al. ([14]) found that the coarse fraction (very coarse and coarse sand) of deposits decreased with distance although the fine fraction (fine sand) varied little with distance. Classifying particle size into two or three parts, such as coarse, fine, and muddy fractions, is considered to be effective in clarifying deposits' spatial variation.

The particle size of the deposits increased with depth at K-1, similar to results reported in [8] and [9]. This is considered to be the result of the difference in settling velocity that occurs as particle size changes as described by Stoke's law. This increase in particle size with increasing depth becomes clearer over time because the surface deposits roll up and settle again and again when ponding occurs after heavy rains. The material at the surface at K-1 included about 10% of fine fraction (< 0.1 mm) particles, suggesting that muddy material

Table 1 Location and thickness of the tsunami deposits at the research sites

Site name	Kashima			Shibusa	
	K-1	K-2	K-3	S-1	S-2
Longitude	37° 41 ' 29"	37° 41 ' 49"	37° 41 ' 59"	37° 38 ' 15"	37° 48 ' 28"
Latitude	141° 0 ' 28"	140° 59 ' 46"	140° 58 ' 51"	141° 0 ' 56"	140° 59 ' 55"
Distance from shoreline (m)	300	1300	2700	700	2200
Thickness of deposit (m)					
muddy deposit	-	-	0.05	-	0.05
sandy deposit	0.25	0.10	-	0.05	0.05

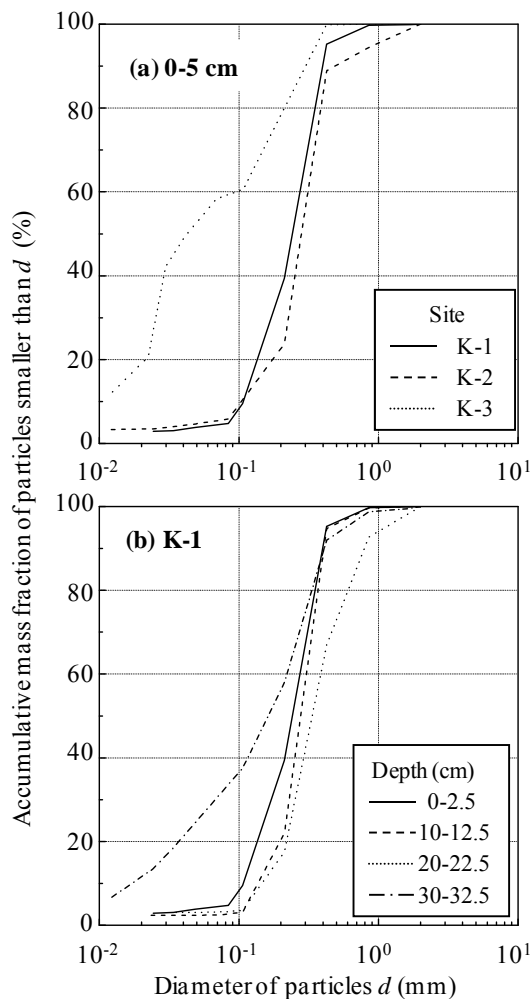


Fig. 2 Particle size distribution of deposits

was mixed in the deposits in the coastal area even though the deposits appear to be sand.

3.3 Water Content and Bulk and Particle Densities of the Deposits

The deposits tended to contain less water than the paddy soil underneath (Table 2). Sandy deposits in the surface layer were particularly dry, with a water content of about 10%. The bulk density of the sandy deposit at the surface at K-1 was 1.6 Mg m^{-3} , which is 1.8 times the density of the muddy deposits at K-3 and S-2 (about 0.9 Mg m^{-3}). The bulk densities of the paddy soils tended to decrease with the increasing of the distance from shoreline, but those near the surface was not always larger than those at deeper layer. Compaction by the deposits overlying the farmland surface soil was not recognized from the measurements of bulk densities. The compaction caused by those deposits should be comparatively small since the surface soil of the paddy fields in this area is heavy clay and drainage before the tsunami event had already consolidated it. On the other hand,

Table 2 Water content, densities, and ignition loss of deposits

Sampling depth* (m)	Deposit/soil type**	Water content (%)	Bulk density (Mg m^{-3})	Particle density (Mg m^{-3})	Ignition loss (%)
Kashima					
0-0.05	sandy	10.0	1.59	2.95	2.1
K-1 0.10-0.15	sandy	13.0	1.69	2.93	0.7
0.20-0.25	sandy	13.9	1.66	3.03	0.9
0.30-0.35	paddy	26.3	1.24	2.61	9.8
0-0.05	sandy	3.6	1.35	3.01	1.5
K-2 0.10-0.15	paddy	27.3	1.21	2.55	11.0
0.20-0.25	paddy	24.6	1.36	2.61	8.5
0-0.05	muddy	24.6	0.87	2.24	25.6
K-3 0.05-0.10	paddy	25.8	0.97	2.51	12.1
0.20-0.25	paddy	27.5	1.12	2.59	12.2
Sibusa					
0-0.05	sandy	7.7	1.28	2.79	3.6
S-1 0.10-0.15	paddy	31.5	1.15	2.49	13.0
0.20-0.25	paddy	26.4	1.28	2.45	13.9
0.30-0.35	paddy	13.7	0.99	2.70	17.0
0-0.05	muddy	13.7	0.90	2.56	19.6
S-2 0.05-0.10	sandy	23.4	1.14	2.65	6.7
0.20-0.25	paddy	17.0	1.03	2.59	11.1

* depth from the surface of the deposit

** sandy : sandy deposit, muddy : muddy deposit, paddy : paddy soil before tsunami inundation

compression by the deposits can increase over time due to repeated drying and wetting [15]. Since the bulk density of soil, which is related to water infiltration and retention, is an important soil property for agriculture, further measurements are needed to clearly understand the effect of surface soil compaction by the tsunami deposits.

The particle density of the sandy deposits was 2.8 to 3.0 Mg m^{-3} , larger than the density of general farmland soil in Japan ($2.5\text{--}2.7 \text{ Mg m}^{-3}$), while the muddy deposits were less dense (2.2 Mg m^{-3}). The large particle density of the sandy deposits could be due to metal or heavy metal content. Cadmium and chrome concentrations in deposits sampled after the 2004 Indian Ocean tsunami are reported in [16] and [17], whose authors insisted that the heavy metals were not only lithogenic but also anthropogenic. In other words, the metal content of the deposits varies with the types of industry in neighboring areas. Analysis of the metal content of the deposits in this area is necessary. The small particle density of the muddy deposits is interpreted as indicating high organic content. The ignition loss of the muddy deposits was 25%, higher than the losses in the sandy deposits or paddy soil (Table 2). The organic matter included in the muddy deposit could contain microorganisms that live in the ocean. Some may be toxic to humans. Microbiological analysis of the deposits should be done as a matter of course before they are removed and disposed of to restore the farmland. The ignition

loss of the surface deposits at K-1 (0–0.05 m deep) was higher than that of deposits collected from deeper layers (0.10–0.15 m and 0.20–0.25 m) at K-1. This supports the idea that the deposits in the surface layer at K-1 included a muddy component, even though that site is closer to the shoreline.

3.4 Hydraulic Conductivity of the Deposits

The saturated hydraulic conductivity of the sandy deposits was 10^{-4} to 10^{-3} m s^{-1} , about 10 times that of paddy field surface soil (Fig. 3). The relatively large saturated conductivity of the paddy soil may be due to mixing in organic materials (compost, rice straw, etc.) or sandy soil brought in from another place to improve the physical properties of the surface soil. The hydraulic conductivity of the muddy deposits was, conversely, smaller than that of the sandy deposits. At the surface at S-2, the hydraulic conductivity was about 10^{-7} m s^{-1} . Since the bulk density of the muddy deposits was very low, their pore volume should be relatively large even though they had low particle densities. This contradiction can be explained by the smaller pore size of the muddy deposits caused by small particles included in the deposits. The hydraulic conductivity at K-3 was smaller than for sandy deposits but 10 times larger than that of the deposits at the surface at S-2. Some cracks developed during the drying process on the surface at K-3. It is possible that downward infiltration of rainwater is promoted by such surface cracks.

3.5 EC and Cation Concentrations of the Deposits in Kashima

The electrical conductivity (EC) of the deposits sampled in Kashima ranged from 0.39 to 0.13 S m^{-1} for the sandy deposits and were about 1.3 S m^{-1} for the mud (Table 3). The EC of the muddy deposits at K-3 was very large. These ECs

are relatively higher than the EC of the paddy soil under the deposits ($0.04\text{--}0.29 \text{ S m}^{-1}$). The EC of the paddy soil may rise because highly saline tsunami water infiltrated into the soil from the deposits above.

From IC analysis, we found that both Cl^- and SO_4^{2-} concentrations in the extracted water decreased with depth. The ion contents of the dry material were estimated using the water content of the deposits and the ion concentrations of the extracted water. The estimated Cl^- and SO_4^{2-} contents of the sandy and muddy deposits were 0.5% and 0.05% for sandy deposits and 3% and 0.2% for muddy deposits. These estimated values agree with the results in [17], which reported a Cl^- content of 0.03% to 3.4% and an SO_4^{2-} content of 0.05% to 3.5%.

In [2], salt leaching is said to be necessary when the Cl^- content is larger than 0.1% for paddy fields and 0.05% to 0.07% for upland fields. In this area, the Cl^- contents of both the deposits and the soil exceed those standards. Thus leaching will be needed before the field can again be used as agricultural land after the deposits have been removed. Only that of the paddy soil at K-2 at depths from 0.20 to 0.25 m was lower than the threshold where leaching is needed. At this site, just removing the tsunami deposits would be enough to restore the farmland, without leaching. But it has also been reported that the peak of ion concentration moves downward with time [10], [17]. Thus, removing the deposits, including any toxic substances they carry, should be completed as soon as possible to prevent contamination of the soil below.

3.6 Estimation of the Volume of the Deposits in Kashima

The total volume and mass of the deposits in Kashima was estimated using the measured depths and the bulk density of the deposits (Fig. 4). The shape of the area, the bulk density of the deposits and the relationship between the distance from the shoreline and the thickness of the deposits were approximated, making the following assumptions:

- 1) The area is approximated by a trapezoid whose upper base is 2,100 m, bottom base is 4,500 m, and height is 2,900 m.

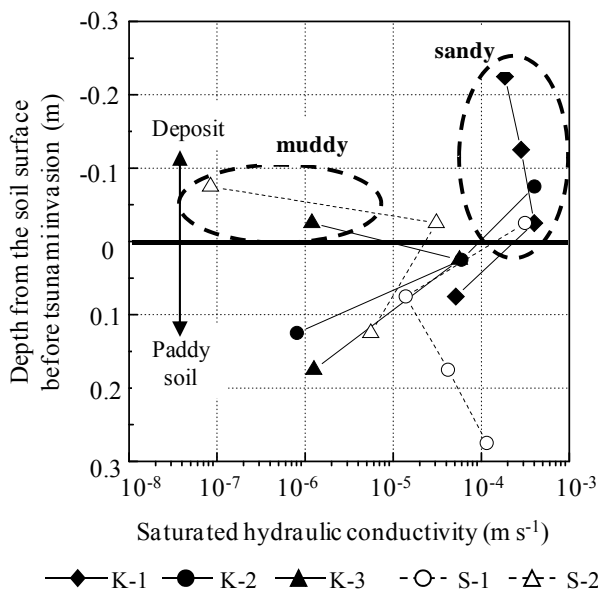


Fig. 3 Distributions of saturated hydraulic conductivity

Table 3 EC and Cl^- and SO_4^{2-} contents of the deposits

	Sampling depth (m)	Extracted water			Dry soil base	
		EC (S m ⁻¹)	Cl ⁻ (ppm)	SO ₄ ²⁻ (ppm)	Cl ⁻ (mg g ⁻¹)	SO ₄ ²⁻ (mg g ⁻¹)
K-1	0-0.05	0.25	1070	422	5.6	2.2
	0.10-0.15	0.39	750	82	4.5	0.5
	0.20-0.25	0.25	750	80	4.2	0.4
	0.30-0.35	0.17	460	33	3.0	0.2
K-2	0-0.05	0.21	590	57	3.9	0.4
	0.10-0.15	0.13	410	50	2.2	0.3
	0.20-0.25	0.04	100	4	0.6	0.0
K-3	0-0.05	1.28	4830	309	28.4	1.8
	0.05-0.10	0.29	680	132	4.5	0.9
	0.20-0.25	0.14	370	65	2.3	0.4

- 2) The bulk density of the deposits is 1.66 Mg m^{-3} for sandy deposits and 0.88 Mg m^{-3} for muddy deposits.
- 3) The thickness of the deposit depends only on the distance from the shoreline. The thickness of the sandy deposits decreased and that of the muddy deposits increased linearly with distance.
- 4) Only sandy deposits were laid down at K-1 (300 m from shore) and muddy deposits at K-3 (2,700 m). The thickness of these deposits was 0.25 m at K-1 and 0.05 m at K-3, respectively.
- 5) The material deposited on the surface at K-2 to a depth of 0.05 m was assumed to be a mixture of sandy and muddy deposits. The mixing ratio was calculated by doing interior division of the assumed bulk densities of sandy and muddy deposits and the measured bulk density of the surface deposits. The mixing at K-2 was calculated to be 0.60. The thickness of the sandy deposits at the surface was then 0.03 m and that of muddy deposits was 0.02 m deep. The material lying from 0.05 m to 0.10 m deep at K-2 is

assumed to be sandy.

The relationship between the distance from the shore (x m) and the width of the area (Y m) was obtained based on assumption 1:

$$Y = -0.828x + 4500 \quad (1)$$

The relationships between x and the thickness of the deposits was based on assumptions 3, 4, and 5, where y_1 is the thickness of the sandy material and y_2 is the thickness of the muddy material:

$$y_1 = -0.00017x + 0.30 \quad (x < 1770) \quad (2)$$

$$y_2 = 0.0000021x - 0.08 \quad (x < 370) \quad (3)$$

By multiplying the area and the thickness of the deposit, the total volume of the deposits was estimated to be $124,000 \text{ m}^3$ (sandy deposits: $106,000 \text{ m}^3$; muddy deposits: $18,000 \text{ m}^3$). The total dry mass, estimated by multiplying the volume by the bulk density of the deposit was $193,000 \text{ Mg}$ (sandy deposits: $176,000 \text{ Mg}$; muddy deposits: $17,000 \text{ Mg}$). To estimate the results more precisely, further measurements of the thickness and density of the deposit in the area are needed. Wave height and tsunami speed, which affect the amount of tsunami deposits, can be used to estimate the amount of the deposits more accurately [13]. On the other hand, no clear relation between distance and thickness was observed in Shibusa. To estimate the total volume of material deposited in this area it is necessary to learn more about the microtopography of the area and the sea base in front of it because not just microgeographical features of the ground but also spatial variability of seabed properties can affect the amount and properties of the deposits.

4 CONCLUSION

To clarify the physical and chemical properties of the tsunami deposits caused by the Tohoku-Kanto earthquake on 11 March 2011, field research and measurements of several properties were done in Minamisoma City located in northeastern Fukushima Prefecture. Two kinds of deposits, sandy and muddy, were observed. The sandy deposits, which had larger particles, were observed in the area near the seashore. The deposit was a maximum of 0.25 m thick, thinning as the distance from the shoreline increased. The particle density of the deposit exceeded 2.8 Mg m^{-3} , which indicated that metals and/or heavy metals might be present. The hydraulic conductivity of the deposits was large although their bulk density was also large. Rapid infiltration is likely to promote downward transfer of toxic materials from the deposits into the farmland soil. The muddy deposits, found distributed farther from shore, had smaller particles and were less dense. The maximum thickness of these deposits was

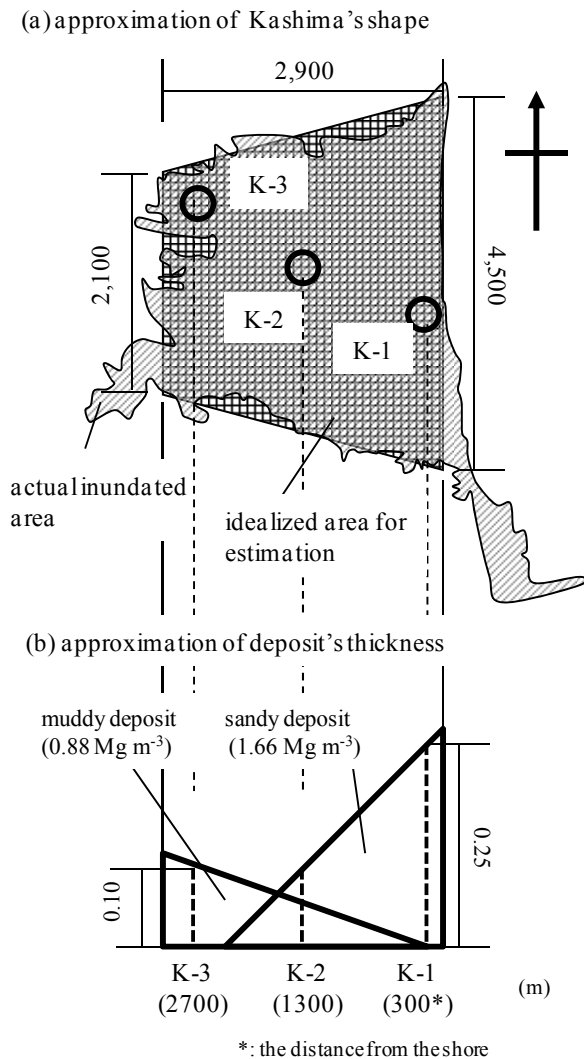


Fig. 4 Schematic diagram for estimating the volume and mass of the deposits

0.05 m. The particle density was low and they contained large amounts of organic matter, which suggested that there may be microorganisms or their products contained in the small, dry particles of the deposits that could be harmful to humans. The electrical conductivity of the muddy deposits at Kashima was very large. There were large cation concentrations in water extracted from these deposits, indicating that they also had large anion concentrations. The Cl⁻ contents of both the deposits and the soil exceed the standards established by the government. It indicates that leaching will be needed before the field can again be used as agricultural land after the deposits have been removed. Using approximations of the shape of the area and the bulk density and thickness of the deposits, we estimate that 124,000 m³ of deposits were laid down in the study area, having a mass of 193,000 Mg. The thickness of the deposit in Shibusa, about 3,000 meters from Kashima, did not increase with increasing distance from the shoreline, suggesting and that the characteristics of the deposits differed from location to the location. To apply the obtained results to other areas, further investigations of the properties of the deposits are needed and especially the information about time and spatial variability of them are expected.

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