Water content, organic carbon and dry bulk density in flooded sediments

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Abstract

Several basic properties of pond bottom soil are shown to be related, a relation that enable to evaluate pond bottom soil characteristics through the determination of one parameter (e.g. soil moisture). In addition, these relationships give some insight into the properties of flooded sediments. Unlike terrestrial soils, made of gas, liquid and solid phases, flooded sediments are made practically of only two phases, liquid and solid. Since all voids are filled with water, it is possible to evaluate soil porosity and bulk density, directly from the moisture content of the soil, a property easily determined. The correlation between bulk density and organic matter was tested in six different systems (n = 868), including rivers and fish pond sediments in Israel, fish pond sediments in Alabama, USA, and Abbassa, Egypt, lake sediments in New Zealand, alpine lake sediments in Colorado, USA, and sea floor sediments from the Northwest African continental slope. Sediment bulk density was inversely related to the organic carbon concentration. The regression for all the data points was:

Bulk density (g/cm³) = 1.776 − 0.363 Log_e OC  \quad (R^2 = 0.70)

where OC is the organic carbon concentration (mg/g). The relationship between sediment moisture, bulk density and organic carbon described here can be used as a simple means to estimate the organic content and bulk density of flooded mineral soils by a simple determination of a sediment water content. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Sediment; Organic carbon; Water content; Dry bulk density; Porosity

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1. Introduction

Inter-relationships and dependency among water content, organic matter concentration, dry bulk density and porosity of waterlogged sediments is demonstrated in this paper. Knowing the value of any one of these properties enables to estimate the other ones.

The sediment–water interface is a transition zone between the water and the underlying soil, a region affecting processes in different water bodies such as oceans, estuaries, lakes, reservoirs, rivers, fish ponds, waste water stabilization ponds and others. The surface is constantly affected by the deposition of allochthonous and autochthonous organic matter. Organic matter (OM) content increases with time before it reaches a steady state, depending on the accumulation and decomposition rates (Avnimelech, 1984; Avnimelech and Wodka, 1988). The percentage of OM is one of the basic properties of the sediment and is related to other important properties of the sediment such as the density of heterotrophic microbial community (Krichman and Mitchell, 1982), adsorption capacity toward organic components and pollutants (Sposito, 1989) or the sediment oxygen demand (SOD). Biochemical oxygen demand (BOD) is related to the concentration of OM (expressed often as chemical oxygen demand, COD), a relationship that is used for the design of biological waste-water treatment units. Boyd et al. (1978) related the oxygen demand of pond water to the concentration of organic carbon.

Water content, bulk density and porosity are important properties of soils and bottom sediments. It is important to note that in flooded soils, unlike terrestrial soils, these properties are uniquely inter-related. Terrestrial soils are complex and time dependent matrix of solid, liquid and gaseous phases. Flooded soils contain practically only two phases, namely solid particles and water that fill up all the pores. In cases, there are some gas bubbles entrapped, yet these are of minor importance as to the bulk properties of the sediment. The presence of only two phases leads to an intrinsic dependence among water content, bulk dry density and porosity.

Dry bulk density is the mass of dry solids in a given bulk volume of soil (Brady, 1984).

\[
\text{Dry bulk density (g/cm}^3) = \frac{\text{Weight, Dry sample (}W_d\text{)}}{\text{Total sample volume (}V_t\text{)}}
\]

\[
\text{Dry bulk density } = \frac{(W_d)}{(V_t)} \quad (1)
\]

It is important to emphasis the difference between particle density (i.e. the weight of a dry sample divided by the volume of the particles) and the dry bulk density. In hydrated sediments (e.g. the flocculent layer), there are only a few percents of dry matter in a given volume and the bulk density is often appreciably lower than one. Munsiri et al. (1995, 1996), reported dry bulk density of 0.25–0.3 g/cm\(^3\) in the surface layer of fishpond bottom soils. The dry bulk density is related, directly or indirectly to the softness (or hardness) of the sediment, its vulnerability to erosion, resuspension and other mechanical properties.
The total volume of a sediment sample \( V_t \) is equal to the sum of the volume of the solids \( V_s \) plus the volume of the water \( V_w \), assuming that water density is 1 g/cm\(^3\):

\[
V_t = V_s + V_w = \left( \frac{\text{weight dry sample}}{\text{sediment particle density}} \right) + (\text{weight wet sample}-\text{weight dry sample})
\] (2)

Inorganic sediment particle density is in the range of 2.6–2.7 and is conventionally taken as 2.65 g/cm\(^3\) (Blake and Hartge, 1986a; Boyd, 1995). The average particle density of sediment containing significant fraction of organic particles can be corrected assuming a density of 1.25 g/cm\(^3\) for the organic particles (Boyd, 1995):

\[
\text{Weighed average sediment particle density (g/cm}^3\) = (1.25 (% organic matter) + 2.65 (100%-% organic matter))
\] (3)

Normally, for OM concentrations of up to 5%, as found in most pond sediments (Boyd, 1995), this correction is negligible. The average particle density is reduced from 2.65 to 2.62, 2.58 and 2.51 g/cm\(^3\) for 2, 5, and 10% OM, respectively.

The bulk density is calculated by inserting the soil volume calculated with Eq. (2) into Eq. (1). The dry bulk density in flooded soils is primarily affected by the water content.

An another important characteristic of sediments is the porosity, the percentage of the total volume not occupied by solid particles. In flooded sediments this is equivalent to the volumetric percentage of water in the sediment. The porosity of the sediment, \( \rho \), is equal to:

\[
\rho = 100 \times \left( \frac{V_w}{V_t} \right) = 100 \times \left( \frac{V_t - V_s}{V_t} \right)
\] (4)

The porosity of the sediment can be also calculated through the relationship between its dry bulk density and the particle density (Danielson and Sutherland, 1986):

\[
\text{Porosity} = \left( 1 - \frac{\text{bulk density}}{\text{particle density}} \right) \times 100.
\] (5)

Obviously, the porosity in the case of flooded sediments is easily approximated knowing the water content.

The porosity affects the diffusion and transfer of dissolved species between the sediment and the overlying water. Diffusion of dissolved substances within the sediment takes place only in the pores and thus is approximately linearly depended on porosity. The diffusive flux \( J_i \) of a certain dissolved substance can be calculated from Fick’s first law adapted to conditions existing in flooded sediments (Berner, 1980):

\[
J_i = D_i \frac{dC}{dx} = D_o \times p \times \frac{dC}{dx},
\] (6)
where \( J_i \) is the flux; \( D_o \) and \( D_s \) are the diffusion coefficient for the particular diffusing substance in the water and the sediment, respectively, \( \rho \) is the porosity of the sediment, and \( \frac{dC}{dx} \) is the concentration gradient (Berner, 1980).

In this work we tested the relationship among water content, sediment bulk density and porosity on one hand with the OM contents of the sediment, using data obtained in fishponds, lakes and rivers in Israel, Egypt, the USA and New Zealand, Alpine lake in the USA and sea floor sediments from NW Africa.

2. Materials and methods

OM concentrations, wet bulk density and water contents were determined in non-disturbed sediment cores taken in a number of rivers in and in earthen fishponds in Israel. Cores from 0 to 20 cm depth were cut into slices of known depths, weighed and dried at 65°C. Organic carbon concentrations were determined using a potentiometric titration following a di-chromate oxidation (Raveh and Avnimelech, 1972).

Same parameters were taken from literature data, representing lake sediments in New Zealand (Hamilton and Mitchell, 1997), earthen fishponds in Alabama, USA (Munsiri et al., 1995) and Abbassa, Egypt (Munsiri et al., 1996), Alpine lake sediments in Colorado, USA (Menounos, 1997), and sea floor sediments from the Northwest African continental slope (Thiede et al., 1982).

When needed, organic matter (OM) data were converted to organic carbon (OC) using the conventional conversion (Brady, 1984; Boyd, 1995):

\[
\text{OM} = 1.7 \times \text{OC}
\]

The total number of data points analyzed was 868, with an organic carbon contents ranging from less than 1 mg organic C/g up to about 100 mg C/g.

The regression analysis of the data was made using SPSS statistical package (SPSS, 1993).

3. Results and discussion

The dry bulk density values of the 868 data points are plotted vs. the logarithm of the respective organic carbon contents in Fig. 1.

The relationship between the two variables is described by a logarithmic equation:

\[
\text{Bulk density (g/cm}^3\text{)} = 1.776 - 0.363 \log_{10} \text{OC}, \quad R^2 = 0.70,
\]

where OC is the organic carbon concentration (in mg/g). The different data points are all in a reasonable agreement with the calculated line, though they differed much in location, composition and climate.

The variation becomes smaller for given individual systems, as for example (Fig. 2), the data set for alpine lake sediments (Menounos, 1997) with an \( R^2 = 0.89 \). The
correlation in other individual systems was also good, $R^2$ being 0.79, 0.77 and 0.81 for fishpond sediments in Alabama and Egypt and river bottom soils in Israel, respectively. The lower correlation for the universal relationship between OM and density may be due to size distribution or surface area of the inorganic particles, a factor that affect OM adsorption capacity (Mayer, 1994).

Others obtained similar results. Menounos (1997) found a statistically significant relationship between OM and dry bulk density in deep cores of alpine lake sediments. He suggested to use this relationship for paleo-environmental reconstruction. Håkanson (1977) found a very close relationship between OM and water content in sediment samples taken along cores of 0–10 cm in Lake Ekoln, Sweden. Håkanson and Jansson (1983) calculated a relationship between the sum of the

Fig. 1. Bulk density vs carbon for 868 sediment samples from six different locations world wide.

Fig. 2. Bulk density of sediments as a function of organic carbon concentration. Data from Holocene Lake sediment (adapted from Menounos, 1997).
Table 1

<table>
<thead>
<tr>
<th>Organic matter concentration (% weight)</th>
<th>Bulk density calculated as affected by dilution (g/cm³)</th>
<th>Bulk density according to experimental relationship (g/cm³)</th>
<th>Porosity derived from experimental relationship (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>1.776</td>
<td>1.776</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>1.771</td>
<td>1.192</td>
<td>55</td>
</tr>
<tr>
<td>1.0</td>
<td>1.767</td>
<td>0.94</td>
<td>64</td>
</tr>
<tr>
<td>5</td>
<td>1.729</td>
<td>0.356</td>
<td>87</td>
</tr>
</tbody>
</table>

water and the OM contents with the wet bulk density, a relationship that can hold only for relatively high water content.

Several mechanisms can be assumed to explain the relationship between dry bulk density and OM concentration. The effect of OM on the reduction of dry bulk density in terrestrial soils was extensively studied (e.g. Khaleel et al., 1981; Clapp et al., 1986). However, unlike terrestrial soils in which the added OM induces and stabilizes aggregates, the flocculent layer in aquatic bottom soil has no aggregation but approximates a homogeneous sludge.

A different explanation may be based on the addition of light OM to the soil. The particle density of OM, having an average density of 1.25 (Håkanson and Jansson, 1983; Boyd, 1995) is lower than that of inorganic sediment that has an average density of 2.65 g/cm³ (Brady, 1984). It can be assumed that the addition of lighter material decreases the weighed average density. The decrease in bulk density by adding 0–5% OM was calculated and the results are given in Table 1, in comparison to the experimentally derived bulk density values. Obviously, the effect of a simple addition of lighter OM is a minor one and cannot explain the observed relationship.

The effect of the added OM on the bulk density of the sediment becomes clearer if we consider the possibility that the OM is highly hydrated. The dry bulk density of hydrated microbial biofilms, containing only few percents of dry matter in a matrix of water is in the range of 0.01–0.1 g dry matter/cm³ (e.g. Christensen and Characklis, 1990). It is plausible, that a significant fraction of the OM found in sediments is comprised of a microbial consortia similar to the hydrated biofilms. Thus, even 1% by weight of organic hydrated matter may double the volume of the sediment and certainly reduce its bulk density. The structure of mineral aquatic bottom soil (especially bottom soil made of fine silt and clay particles) may be conceptualized as mineral particles spaced apart by organic micelles.

The dependence of dry bulk density on the OM is related to several important properties of the pond bottom. One known phenomenon is the evolution, with time, of a soft flocculent layer in the pond bottom. Fresh pond bottom (newly built ponds or ponds following drainage and drying periods), is usually hard. Yet, with the accumulation of active hydrated OM, it tends to get soft and flocculent. A decrease of OM with depth is typical in ponds and other aquatic systems bottom
soils. OM is added onto the surface of the bottom soil by sedimentation from the water body. The deep layers are disconnected from this OM supply. The decomposition process leads to a decline of OM concentrations with depth, probably a marked decline of active hydrated OM, and to an increase of bulk density with depth. A density and porosity gradient with depth down to a constant density is typical (e.g. Hakanson and Jansson, 1983; Munsiri et al., 1995, 1996). Munsiri et al. (1995) determined the density of several sediment layers in fishponds. The thickness of the low-density top layer increased with the increase of pond age, as did the organic carbon content.

According to Eq. (8), the bulk density of flooded sediments having a very low organic carbon content (1 mg/g) is equal to 1.776. This is a very high bulk density, as compared with ordinary, non flooded soils, having normally a density range of 1–1.6 g/cm³ (Brady, 1984). Terrestrial soils are structured, made of aggregates and usually contain a significant fraction of large voids. In contrast, aquatic sediments are practically structure-less and are being compacted when the spacing among particles induced by the hydrated organic micelles disappear. This is in accordance with common knowledge and experience regarding the development and presence of dense impermeable sub-soil layers in ponds and other aquatic systems.

The topmost layers of the bottom soils are enriched with OM and have a very low density. Cohesion at the sediment surface is low and a flocculent layer above the surface is commonly found (D’Angelo and Reddy, 1994; Hargreaves, 1995). These layers are fluffy, have low cohesion and a very high porosity. The last column in Table 1 gives the porosity as it increases with the level of OM. The porosity of the sediment samples having more than 5% organic carbon is higher than 80%. According to Eq. (6), diffusion coefficients in such sediments are almost as high as those existing in free water, a result that is of importance as to transfer of materials between the bottom soil and the overlying water.

4. Conclusions

This work deals with a few very basic properties of aquatic sediments: water content, organic matter levels, dry bulk density and porosity. These affect other basic characteristics and processes such as diffusion, mechanical properties of the soil and microbial metabolic rates.

This work leads to a number of both practical and theoretical conclusions.

One very practical conclusion is that a simple determinations of water content (or OM if this can be easily done), can give a wide range of data approximating some of the most important properties of the sediment.

Though OM in pond bottom soils is not a major component, it was shown to have a very important role in determining the water content, density and porosity of sediments. This dependence seems to reveal a structural dependence of sediments on the coating and spacing of inorganic particles by hydrated OM.

The similar response of aquatic sediments in ponds, rivers and lakes, in different climatic and edaphic regions, suggest that conclusion drawn from our study have a
practical applicable value in a wide range of aquatic systems — including aquaculture.

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References