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A method for measuring effects of bioturbation and consolidation on erosion resistance of aquatic sediments

Luis Zambrano[1], John Beijer[2], Frank Roozen[2] and Marten Scheffer[2] *

With 7 figures

Abstract: Sediment erosion by water movement affects turbidity and thus benthic communities in numerous aquatic systems. This aspect has been widely studied in coastal habitats and estuaries, but less studied in freshwater systems such as shallow lakes. Here we present a simple device to study the effects of biota on the resistance of aquatic sediments to erosion by water movement. Circular 75 l tanks are used to incubate selected sediments with microbial communities. The tank size allows addition of organisms such as small fish, invertebrates and aquatic plants. Effects are studied by gradually increasing water movement by means of a rotor and continuously monitoring the increase of suspended solids. The water speed needed for resuspension is a measure of sediment erosion resistance. With this device we found a linear increment of erosion resistance over time if sediments are left undisturbed, and a significant reduction of erosion resistance with small holes punched randomly in the top layer of sediment (to mimic the effect of benthivorous fish foraging behaviour). Fish biotic perturbation was indicated by a reduction of sediment resistance associated with benthivorous fish presence. However, three spined stickleback did not create the same effect. Measurements with this simple device are reasonably precise and suggest that the set-up can be used to study effects of numerous factors that may affect sediment erosion resistance. For example, sediment consolidation associated with light, temperature, and microbial and plant colonization, along with sediment perturbation related to big invertebrates and fish behaviour.

Key words: sediment erosion, sediment resistance, bioturbationm microbial colonization.

[1] **Authors' addresses:** Departamento de Zoología Instituto de Biología, UNAM, Apartado Postal 70-153, México D. F. 04510. México;
E-mail: zambrano@ibiologia.unam.mx

[2] Department of Aquatic Ecology and Water Quality Management, Agricultural University Wageningen, P. O. Box 8080, NL-6700 DD Wageningen, The Netherlands.

* Corresponding author; E-mail: Marten.Scheffer@wur.nl

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Introduction

Turbidity and nutrient dynamics in shallow lakes are strongly affected by sediment-water interactions (Hosper 1994, Hamilton & Mitchell 1997, Scheffer 1998), particularly the resuspension of sediments by water movement (Kristensen et al. 1992, Couperthwaite et al. 1998, Vos et al. 2000). For example, in shallow lakes more than 85 % of sediment resuspension is produced by water currents close to the lake bed (Evans 1994). These implications have produced a vast literature on the effect of resuspension on the water column (Carper & Bachmann 1984, Aalderink et al. 1985, Bengtsson & Hellstrom 1992).

Resuspension of sediments by moving water occurs rather suddenly once a critical shear stress is exceeded. This shear stress depends on the roughness of the sediment, water depth, and wave size. The latter increases with wind speed and the length of the stretch of water over which the wind is blowing ('fetch'). Thus the larger and the shallower a lake, the higher the shear stress on windy days and the more likely that wave resuspension occurs (Scheffer 1998).

Although these processes driving water movement along the sediment are all relatively well understood, it has remained difficult to assess the effect of processes which determine sediment firmness, and thus the critical shear stress that can be resisted before erosion occurs. It is well known that the critical shear stress depends on sediment type, but also increases over time if the sediment is left undisturbed (Scheffer 1998). Such consolidation is due to physical processes and to the often-rapid development of a community of benthic algae, bacteria and other micro-organisms at the sediment surface (Delgado et al. 1991, Wright et al. 1997, Tolhurst et al. 1999, Prochnow et al. 2001). On the other hand, perturbation of sediments by benthivorous fish or other organisms can strongly reduce the critical shear stress needed to resuspend sediments (de Deckere et al. 2000, Scheffer et al. 2003). Although such biotic impacts on sediment resistance against erosion are likely to be large, they are poorly understood, in part because it is difficult to measure erosion resistance in realistic situations. Here we present a device for measuring sediment erosion resistance and demonstrate its use by analyzing the effect of consolidation and of local disturbances on the resistance of sediments to erosion by water movement.

Methods

Erosion measuring device

The device consists of two concentric cylinders (60 and 35 cm diameter, 40 cm high) and a rotor (Fig. 1). For our experiments a layer of sediment, based on clay, was in-

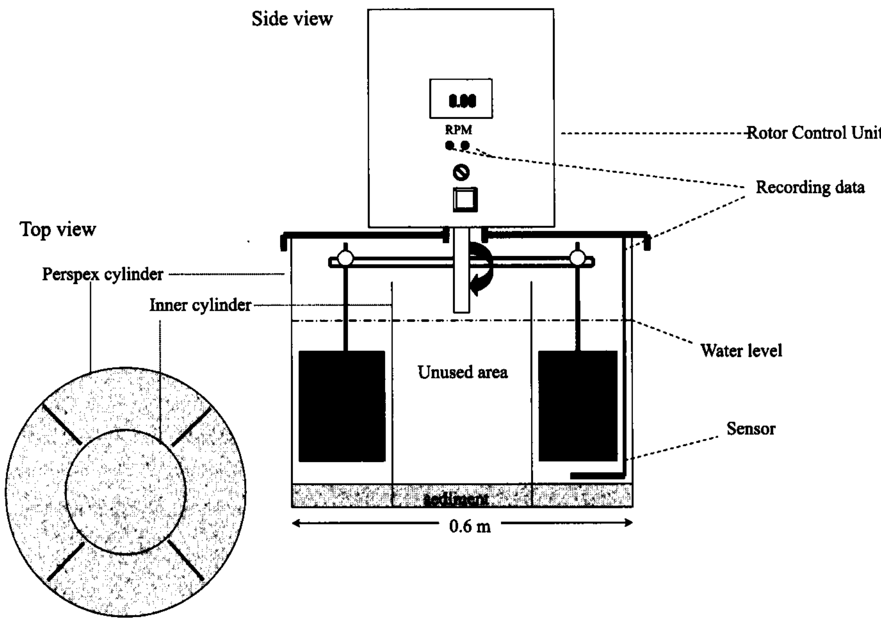

Fig. 1. Experimental set-up used to measure the erosion resistance of the sediments. Rotor speed is gradually increased up to a maximum of 19.3 RPM. The moment at which erosion and resuspension occurs is detected using an infrared light-sensor measuring turbidity between blades and the sediment.

cubated under 40 cm of water within the transparent plastic (perspex) outer cylinder, containing tap water. Just before measurements took place, an opaque plastic inner cylinder was carefully placed on the sediment. Once the inner cylinder was positioned, the electric rotor with adjustable speed was placed on top of the cylinders. Four blades (12 cm wide and 20 cm high) were suspended from the rotor to create a current in the circular channel between the two cylinders. The adjustable blades were totally submerged and positioned 4 cm away from the sediment (see Fig. 1).

Rotor blades and water velocity

Before the experiments started, we explored the relation between water velocity and the speed of the rotor blades. To measure water speed, a magnetic electrode (RC2 by Aqua Data, UK; accuracy 0.5 cm s^{-1}) was situated at the bottom of the cylinder over the sediment surface. The water was left undisturbed for 30 minutes, after which the rotor was started with an initial speed of 1.89 revolutions per minute (RPM) and allowed for an initial stabilization phase of 30 seconds to produce a consistent and uniform current of water. After this initial phase water current velocity stabilized in less than 10 seconds on each of the incremental steps. Then rotor speed was increased by 0.3 RPM each 15 seconds in a step-wise fashion, until the maximum rotor speed (19.3 RPM) was reached.

The circular shape of the channel implies that water current speed should be higher close to the outer cylinder than to the inner cylinder. To check the magnitude of this effect we measured water speed in three positions: close to the inner cylinder, in the middle of the channel and close to the outer cylinder. This process was repeated 5 times in each position.

Sediment resuspension measurements

Once the set was placed on the incubated sediment, an infrared light-sensor was situated between blades and sediments to get a continuously relative measure of the suspended solids concentration in the water column (Fig. 1). A data-logger was used to record RPM increments together with the indicator of the infrared light-sensor values each second. The procedure to increase the water speed was the same as that used to measure the relation between blades and water velocities (see previous section).

Light sensor values that provide an indicator of the relative concentration of suspended solids (T) were plotted against rotor (or water) velocity (V, m s^{-1}) and showed sigmoid relationship (Fig. 2). We fitted a Hill function by means of minimization of the sum of squares:

$$T = T_i + T_r \frac{V^p}{V^p + V_c^p} \tag{1}$$

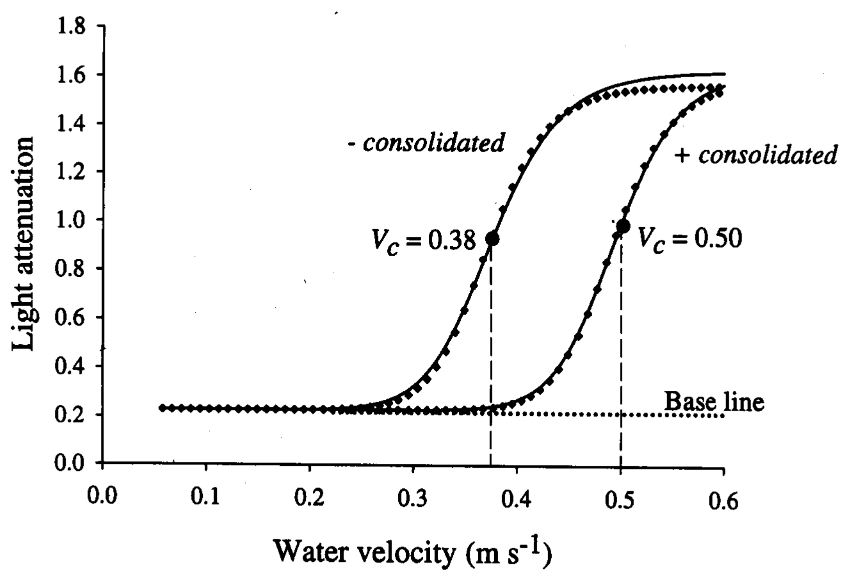

Fig. 2. Turbidity curves obtained by gradually increasing water speed in the experimental set-up (Fig. 1). Curves (eq. 1) were fitted to the experimental data (dots) minimizing the sum of squares and used to obtain an objective indicator (V_c) of erosion resistance of the sediment. In this example, the curve with the $V_c = 38$ (*– consolidated*) describes the response of sediment closer to unconsolidated state, while the curve with the $V_c = 50$ (*+ consolidated*) describes a more consolidated sediment.

where T_i is the turbidity indicator value before erosion, T_r is the maximum turbidity indicator increment due to resuspension, and p gives the sharpness of the curve. The half saturation constant, V_c, approximates the critical water velocity at which erosion increases most steeply. We used this parameter as indicator of the resistance of the sediment to erosion.

Consolidation and perturbation of sediments

We tested our device in a set of seven cylinders. In each tank, we added a layer of 7 cm of mineral clay inoculated with 5 l of mixed mud obtained from the bottom of a eutrophic shallow lake to allow colonization by organisms. To prevent excessive phytoplankton growth we added *Daphnia magna* to each tank. Water temperature was maintained between 20 and 23 °C and the tanks were exposed to a daily regime of 10 hours of dark and 14 hours of light (125 micro einstein m^{-2} sec^{-1}).

Consolidation rates

To analyse consolidation rates, we left the batches of incubated sediment for different periods of time (from 2 to 14 days) and measured the resulting erosion resistance. Each cylinder was used twice, testing different periods of consolidation.

Artificial perturbation and recovery of sediments

To assess the effect of perturbation, we did two series of experiments. In the first series we made artificial holes in sediments which had been incubated for fifteen days. To simulate the effect of benthivorous fish we used a tube to punch the sediment, extracting the sediment captured within it. In a factorial design we evaluated two effects: 1) individual hole size, by mimicking two fish bite sizes (0.6 cm and 1.2 cm diameter), both 2 cm deep, and 2) total disturbed area, by perturbing an area ranging from 0.3 % to 2.5 % of the total sediment area. In a second experimental series we evaluated the recovery time of the sediment. In seven tanks we produced a significant mechanical perturbation (2.5 % of area perturbed) and evaluated sediments recovery with the same technique used for the consolidation rate experiment.

Fish effects on sediment resistance

To examine the effect of biological perturbation on sediment we used nine 1 m^3 tanks (1 m × 1 m × 1 m) prepared with the same type of sediment and water mentioned above. Sediment was left undisturbed for 14 days. Three control tanks (without fish) were compared with three tanks containing 60 g of crucian carp and three containing 60 g of three-spined stickleback. Each tank with carp held three fish (individual weight average ≅ 20 g), while each tank with stickleback held 15 fish (individual weight average ≅ 4 g).

Fish were left for 5 days in the tanks and removed without perturbing the sediments just before the rotor and the cylinders were placed to measure sediment resuspension.

Results

Relation between blade and water speeds

Water movement within the channel is linearly related with blade speed (Fig. 3). The accuracy of the electrode used to measure water speed (see methods section) does not allow the regression to start at the origin. Disparity in water speed values between the inner and the outer part of the flume was small; the differences in water speed only started to be measurable at values higher than 0.4 m s^{-1}. The highest difference of water speed was less than the accuracy of the electrode, and occurred at maximum water speed (0.58 m s^{-1}).

Consolidation, mechanical perturbation and recovery

Sediment resistance was broken at velocities of water flow (V_c) close to 0.3 m s^{-1} in the absence of any time for consolidation. Once the sediments were left to rest, the resistance of the sediment increased linearly with the time from the first day (Fig. 4).

Mechanical perturbation, obtained by punching holes with a tube, resulted in a steep decline of the sediment resistance to erosion (Fig. 5). Holes corresponding to about 2 % of the total sediment surface were enough to reduce the erosion resistance to a value close to the unconsolidated state. The effect is described as a negative exponential equation (Fig. 5). More than 50 % of the ero-

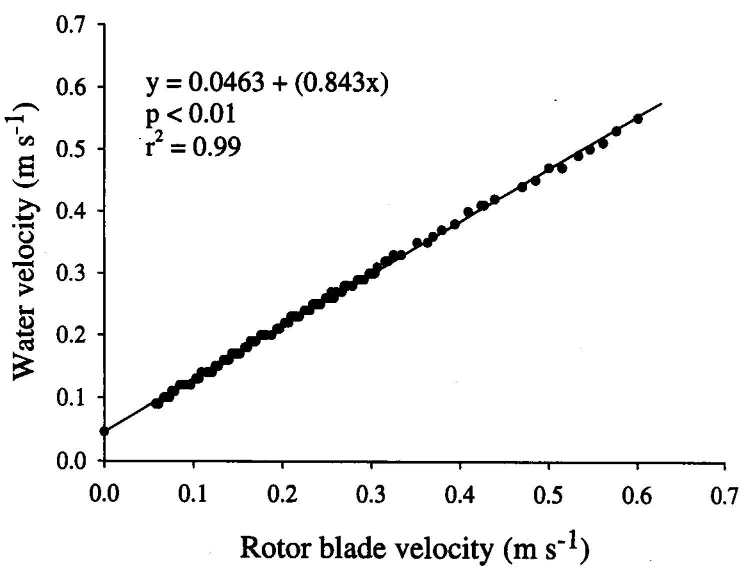

Fig. 3. Relationship between the speed of the rotor blades and measured water velocity at the sediment surface.

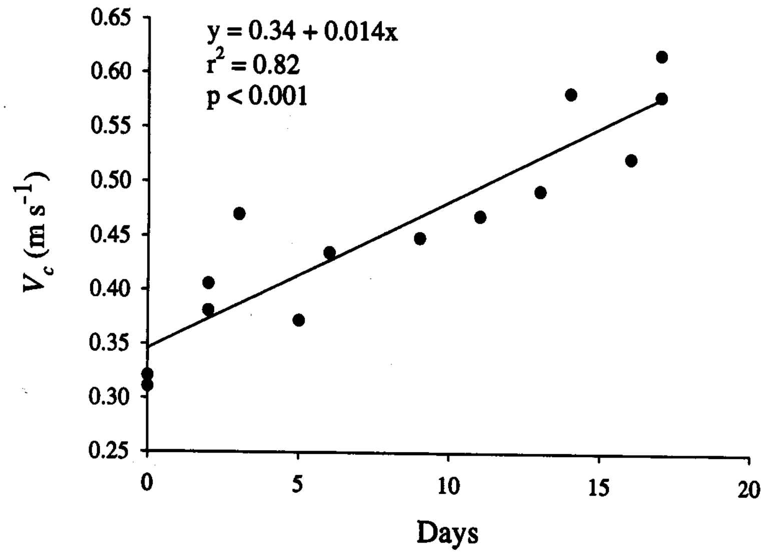

Fig. 4. Erosion resistance, measured as critical water velocity (V_c) needed to cause resuspension, in relation to time allowed for consolidation under the experimental conditions.

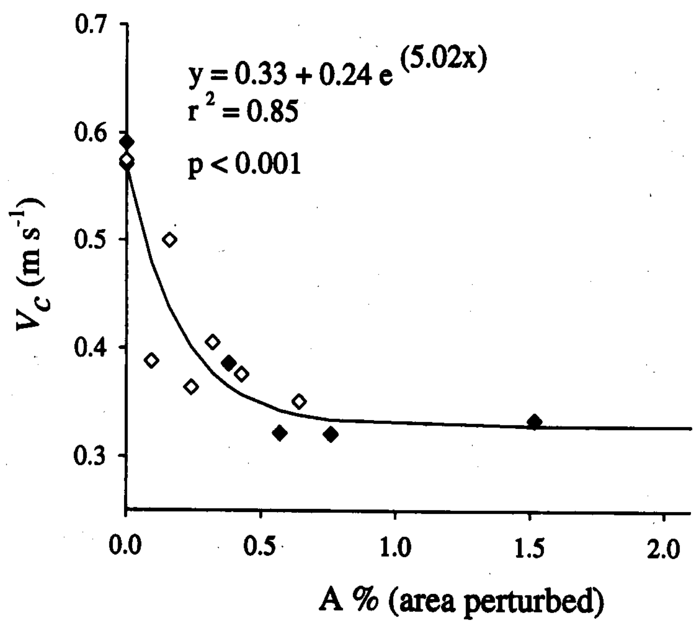

Fig. 5. Effect of manually punched holes on erosion resistance (V_c) of the sediment. Solid diamonds represent holes with an individual diameter of 1.2 cm and empty diamonds represent holes with diameter of 0.6 cm.

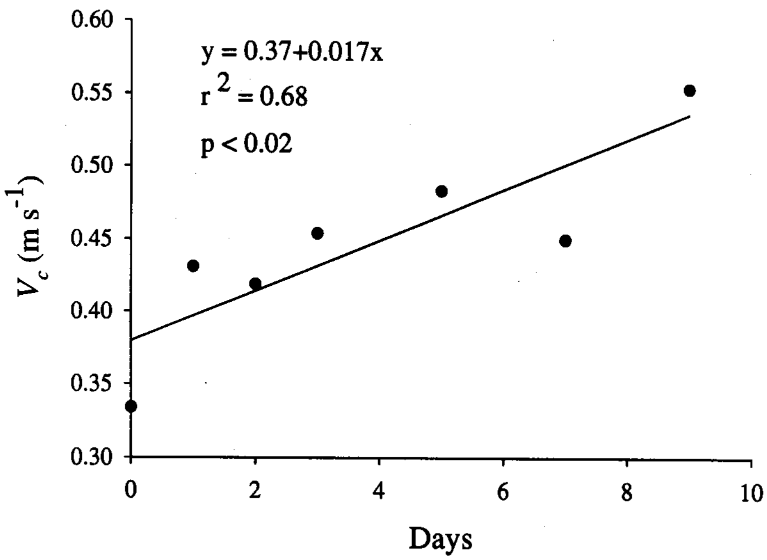

Fig. 6. Recovery of erosion resistance (V_c) due to consolidation after holes were punched at day 0 covering 2.5 % of the sediment surface.

sion resistance acquired by the 2 week consolidation process was eliminated by punched holes corresponding to 0.5 % of the total area. Note that many small holes (empty symbols) have approximately the same effect as a few bigger holes (solid symbols) with the same total surface area.

If sediments with punched holes (but not re-suspended) were left undisturbed, their consolidation recovery required less time to develop (Fig. 6) than the consolidation experiments (Fig. 4). It is possible that the faster recovery of these sediments was related to the rest of the area that was not perturbed. Area perturbed in the punched holes was smaller than the area that has to be consolidated once the experiment starts.

Fish perturbation

Sediment resistance was reduced in presence of carp (Fig. 7). Foraging activity on the fish was based on looking for food at the bottom the tanks. Water turbidity increased from the first day as a result of suspended solids resuspension. The mouth size of three 20 g carp (less than 0.5 cm diameter) was big enough to create holes capable of reducing the critical shear stress of the sediment within five days. However, stickleback did not affect critical shear stress sediment values of the experimental tanks (Fig. 7). Foraging activity of these organisms also was based on searching food on the sediments, but apparently the mouth size was not big enough to create a visible pit in the sediment.

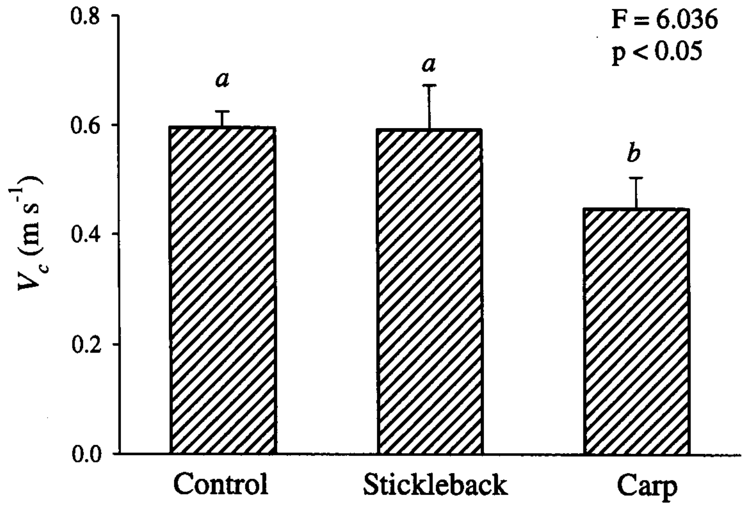

Fig. 7. Mean values of V_c (with standard error) in experimental tanks with or without fish. ANOVA test values are provided. Letters above the bars show pos-hoc test results between treatments (different letters give significant differences while same letter indicates no significant difference).

Discussion

Our experiments illustrate that sediment resistance to erosion may vary strongly with consolidation process and small-scale disturbance of the top-layer as produced by foraging fish. The device we used appears particularly useful to study such processes under controlled conditions. The outside cylinders provide 75 l tanks that are sufficiently large to study effects of biota such as small plants, macro-invertebrates and small fish. The device proved to be useful in generating information using artificial perturbations, but also understanding fish foraging activity within a tank. Results showed that experiments with live animals in this type of systems are possible. While the measurements may not have the accuracy of set-ups used in more precise physical research (Ravisangar et al. 2001, Dey & Debnath 2001), the precision is obviously sufficient to measure important changes in sediment resistance caused by biotic processes addressed in our example. Obviously, we cannot extrapolate the results from our rather unnatural laboratory conditions to field conditions with much precision. Sediments, animal behaviour, water movement patterns and numerous other aspects may differ between the laboratory set-up and field situations. Nonetheless, the relative importance of different processes may be studied under controlled conditions with our device. Such information may be complemented by field studies and model analyses to produce an image of the role of the studied processes in lakes, rivers or marine habitats. An example of such an analysis suggests that benthivorous fish foraging effects are essential to maintain sediments of certain shallow lakes in an unconsolidated state, allowing frequent wave resuspension (SCHEFFER et al. 2003).

We suggest that this approach may be explored further to study effects of numerous factors that may affect sediment erosion resistance. Examples include effects on erosion resistance of different types of sediments (clay, sand, etc.), macrophytes, crayfish, chironomid larvae, and the effect of light and temperature on the microbial consolidation of different types of sediments. Such research would greatly enhance our insight in the potentially large biotic impacts on sediment transport in rivers and resuspension in marine habitats and lakes.

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