International Journal of Sedimentation Research 30 (2015) 100–106

Contents lists available at ScienceDirect

International Journal of Sediment Research

journal homepage: www.elsevier.com/locate/ijsrc

Original Research

Application of a littoral Baltic Sea resuspension model in a eutrophic lake – factors behind differences in the model performance

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A R T I C L E I N F O

Article history:
Received 5 February 2014
Received in revised form
9 September 2014
Accepted 12 March 2015
Available online 6 June 2015

Keywords:
Linear model
Sediment resuspension
Macrophytes
Wind
Sediment quality

A B S T R A C T

The performance of a linear resuspension model developed in the Baltic Sea was studied in the conditions of a eutrophic Lake Kirkkojärvi (southern Finland). The model predicts sediment resuspension rate using data on vegetation cover, wind and sediment quality as an input. When the original model coefficients were used, the model resulted on average 1.8 fold overestimation of the resuspension rate in Kirkkojärvi. This was due to lower fetch and water depth, and less consolidated sediment of Kirkkojärvi compared with the Baltic Sea study site. When coefficients were adjusted for Kirkkojärvi, the model predictions were 1.1 times the measured values. Due to the continuous resuspension, the effect of the wind term in the model was so low that it could be excluded without affecting the accuracy of model predictions. The study demonstrated that in a shallow eutrophic lake accurate predictions on resuspension rate can be made using only data on sediment quality and on factors inhibiting resuspension (macrophytes). The model residuals increased with increasing resuspension rate and high rates of resuspension were underestimated by the model. Due to the fluffy sediment in Kirkkojärvi, erosion of sediment increases more than linear with increasing shear stress. Thus in such conditions, even better predictions could be achieved by a non-linear resuspension model.

1. Introduction

In a large number of water bodies, sediment resuspension induced by wind and wave activity has substantial effects on the water quality and on many biotic processes (Evans, 1994; Weyhenmeyer, 1998). Resuspension can, for instance, strongly affect the rate of primary production through its influence on nutrient concentrations and light environment (Middelburg & Soetaert, 2005; Schallenberg & Burns, 2004; Søndergaard et al., 1992). The resuspension-mediated variations in the concentration of suspended solids and in the light climate also affect zooplankton communities and modify many predator–prey interactions through effects on the reaction distance and behaviour of visual predators (Kirk, 1991; Nurminen et al., 2010).

Sediment resuspension is caused by numerous factors. These include wind-induced waves and currents (Bengtsson & Hellström, 1992; Bailey & Hamilton, 1997), animal activities at the sediment surface (e.g. benthivorous fish) (Breukelaar et al., 1994; Havens, 1991) and human activities such as boat traffic (Yousef et al., 1980; Garrad & Hey, 1987). The effect of such forces on sediment resuspension is again greatly affected by the characteristics of the sediment. Resuspension starts, when shear stress at the sediment surface exceeds the critical shear stress, while the critical shear stress values are highly variable among different sediments (Kleeberg et al., 2010; Scheng & Lick, 1979). For instance, fresh newly deposited organic sediment is more easily resuspended than older and more compacted material (Bengtsson & Hellström, 1992; Niemistö et al., 2008). Water depth is also of importance; resuspension rate is often higher in shallow than in deep areas due to the stronger effect of waves and currents on the sediment in the shallow water (Bloesch, 1982; Evans, 1994). Resuspension rate is reduced by aquatic vegetation that binds the sediment and reduces water flow velocity (James & Barko, 1990; Vermaat et al., 2000; Madsen et al., 2001).

Because of the high number of regulating factors, formulation of models that predict the rate of resuspension from environmental parameters is difficult. Due to the importance of resuspension, numerous attempts have been made and some models have shown to predict wind-induced water quality changes reasonably well (Aalderink et al., 1985; Bailey & Hamilton, 1997; Kristensen et al., 1992). However, aquatic vegetation is still an important source of error in resuspension models and the inclusion of macrophytes in the models requires further studies (Hamilton & Mitchell, 1996; James

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http://dx.doi.org/10.1016/j.ijsrc.2015.03.005
1001-6279/

et al., 2004; Teeter et al., 2001). Effects of aquatic vegetation are complex because different macrophyte species have very variable effects on hydrodynamics and consequently on sediment resuspension, which is again due to large variation in their architecture and distribution in the water column (James et al., 2004; Schulz et al., 2003; Vermaat et al., 2000).

Another problem with resuspension models is that while they may reliably predict resuspension rate at the location where they were formulated, generalization of model predictions to other locations or water bodies is very challenging due to the large spatial variation of the regulating factors (Hamilton & Mitchell, 1996; Scheffer, 1998). Therefore calibration of resuspension models with various data is valuable. Additionally, most models have been developed to predict water quality changes, i.e. the changes in turbidity or concentration of suspended solids from wind and wave effects (Bailey & Hamilton, 1997; Cózar et al., 2005; Hamilton & Mitchell, 1996; Kristensen et al., 1992). Models that predict actual resuspension rates from environmental parameters are more rare. Water quality has a close relationship with resuspension rate (e.g. Scheffer, 1998), but these two parameters do not always fluctuate in unison. For instance, macrophytes may prevent resuspended sediment from mixing to the water column, which can obscure the relationship between resuspension rate and water quality (Horppila & Nurminen, 2005). Another aspect is that to be widely applicable, the models should not be too complex because data for multitudinous parameters are not often available.

Recently, Kaitaranta et al. (2013) presented a simple model that predicted the rate of sediment resuspension when macrophyte density, sediment quality and maximum wind velocity were used as an input. The input data for the model were collected from six different sampling stations in the Western Gulf of Finland, Baltic Sea (59° 50′N, 23° 18′ E). The study stations were moderately eutrophic, average total phosphorus concentration varying from 30 to 40 μg l^{-1}, total nitrogen concentration from 430 to 500 μg l^{-1} and Secchi depth from 1.5 to 2.5 m. The bottom substrate varied from clay to till and organic fraction of the surface sediment varied between 0.5% and 22.6% (Table 1). The stations included locations with emergent and submerged macrophyte stands and areas with no vegetation. Water depth at the sampling stations varied between 1.0 and 1.4 m (Table 1). The average fetch of the sampling locations varied between 90 and 524 m and the maximum fetch between 350 and 6300 m. The emergent macrophyte stands (density 0–60 stems m^{-2}), were formed by common reed *Phragmites australis* (Cav.) Trin. ex Steud., while the stands of submerged species (per cent volume infested (PVI) 0–35%) were dominated by *Potamogeton perfoliatus* L., *Potamogeton pectinatus* L. and *Myriophyllum spicatum* L.

In the present study, the performance of the model by Kaitaranta et al. (2013) was explored in the circumstances of a eutrophic lake. The model was tested with data collected from the Kirkkojärvi basin of Lake Hiidenvesi (Fig. 1). Kirkkojärvi (1.6 km^2, mean depth 1.1 m, max depth 3.5 m), is the most eutrophic part of Lake Hiidenvesi in southern Finland (60° 24′N, 24° 18′E). The average summertime total phosphorus concentration is 80–120 μg l^{-1} and the total nitrogen concentration 1000–1500 μg l^{-1} (Niemistö et al., 2008). Due to resuspended sediments and runoff from the intensively cultivated drainage area, the concentration of suspended solids exceeds 20 mg l^{-1} and Secchi depth is on average < 40 cm (Horppila & Nurminen, 2001; Niemistö et al., 2008). The seasonal fluctuations in the resuspension rate among emergent and submerged macrophyte stands and in the adjacent open water in Kirkkojärvi were reported in Horppila and Nurminen (2001) and Horppila and Nurminen (2003). In the present study, these resuspension data together with data on environmental variables are incorporated in the model by Kaitaranta et al. (2013). Water depth in the sampling stations varied between 0.6 and 1.1 m (Table 2). The average and maximum

Table 1
The average, minimum and maximum values of the model input parameters and observed sediment resuspension rates of the study sites in the Baltic Sea (Kaitaranta et al., 2013).

	Average	Min.	Max.
D_E (stems m^{-2})	11.6	0.0	67.7
D_S (%)	5.9	0.0	35.0
W_M (m s^{-1})	6.3	1.3	13.0
f_R (%)	4.3	0.5	22.6
R (g dw m^{-2} d^{-1})	13.8	4.1	29.2

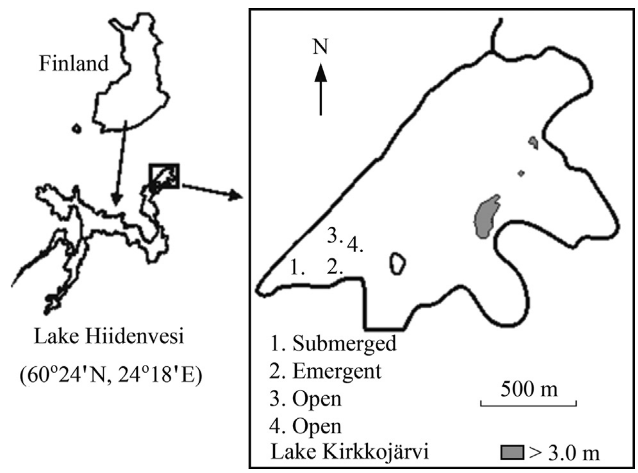

Fig. 1. Lake Kirkkojärvi, its location in Finland and the sampling stations in Horppila and Nurminen (2001) (2, 4) and Horppila and Nurminen (2003) (1, 3).

fetch of the sampling stations were 410 m and 1800 m, respectively. The effects of emergent plants were studied in a stand of narrow-leaved cattail *Typha angustifolia* L., plant density varying from 0 to 22 stems m^{-2} (Table 2). The study on submerged species was conducted in a stand dominated by *Ceratophyllum demersum* (L.), *Ranunculus circinatus* Sibth. and *Potamogeton obtusifolius* Hert and Koch with a 30% maximum PVI (Table 2). The organic fraction of surface sediment varied between 11.4% and 37.3% (Table 2). The study years represented typical circumstances in Lake Kirkkojärvi (Horppila, 2005)

Thus, compared with the Baltic Sea study, the Kirkkojärvi study stations were more eutrophic, less exposed to wind and consequently had higher organic content of the sediment. The lower wind exposure in Kirkkojärvi could be expected to reduce the importance of the wind in the model compared with Kaitaranta et al. (2013), while the role of sediment quality could be stronger in Kirkkojärvi. On the other hand, the lower water depth in Kirkkojärvi could emphasize the effect of wind on resuspension.

2. Materials and methods

2.1. The model

Kaitaranta et al. (2013) predicted sediment resuspension rate in the littoral area of Gulf of Finland, Baltic Sea with the multiple linear regression model:

$$R = \alpha + \beta_1 D_E + \beta_2 D_S + \beta_3 W_M + \beta_4 f_R, \quad (1)$$

where

R = sediment resuspension rate (g dw m^{-2} d^{-1})
D_E = density of emergent macrophytes (m^{-2})